THE IMPACTS OF SEA LEVEL RISE ON THE SOUTH AFRICAN COASTAL ENVIRONMENT

by

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CONTENTS

ABSTRACT

The effects of rising sea levels on the South African coastal environment are investigated with the intention of providing a first step towards identifying and managing the potential impacts of future higher sea levels. Methods suitable for modelling the impacts of sea level rise in South Africa are discussed and a preferred procedure laid out. This procedure is applied to the areas of Woodbridge Island (Cape Town), False Bay (Cape Town), Walvis Bay and Durban and provides a series of detailed case studies or Potential Impact Assessments. These areas are taken to be representative of the major "type-location" environments found around the South African coastline.

The application of a regional vulnerability index, intended for global usage, is discussed and found to be inadequate for the South African Scenario. Based on the findings of the case studies a new vulnerability index is developed which provides a quasi-economic rating for risk to sea level rise. This new coastal vulnerability index is applied to the southern Cape and Natal south coasts; areas of contrasting geomorphology but comparable population densities. The findings from these exercises are extended to the whole coastline and a national vulnerability to sea level rise is built up. Over 80% of the South African coastline is made up of sandy beaches and mobile dunefields and therefore has an obvious potential for coastal damage. After considering levels of population pressure on the coast, those most vulnerable environments are found to include tidal inlets and locations where development has taken place on the primary dunes. Over 60% of the Cape coast's major inlets and estuaries contain significant development which may be susceptible to the impacts of sea level rise. Over-development of the primary dune can be demonstrated in most coastal towns and cities and dune development is particularly prevalent along the Natal south coast and Greater Durban area. Overall four areas of particular risk stand out:

Greater Cape Town. Melkbosstrand to Gordon's Bay.
South Cape coast. Mossel Bay to Nature's Valley.
Port Elizabeth.
Natal south coast and Greater Durban. Southbroom to Ballitoville.

Coastal management policies from a number of countries dealing with sea level rise are discussed and their applicability to South Africa is considered. On the basis of these comparisons it is suggested that South African sea level rise policy should be

instituted on two levels: On a state governmental level, all relevant government departments should acknowledge the overall problem and potential risk from global warming and associated sea level rise. In doing so planners and coastal engineers would be forced to recognize their professional responsibility in this area. On a local government level, any management plan proposed in a recognized sensitive environment or area, should be subject to a sea level rise hazard test. It is suggested that this procedure forms an integral part of the Integrated Environmental Management policy recently being adopted by land use managers in South Africa. Additional studies are necessary to enhance sea level rise management in South Africa. Suggestions for further research include: an improvement in the quantity and quality of the baseline sea level observations; monitoring of coastal processes that may be symptomatic of sea level rise; and investigation into the most effective responses and precautions to take against sea level rise. In this way, the a coherent and practical strategy for dealing with sea level rise may be developed beyond this first management step.

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Chapter 1

INTRODUCTION

The discovery and interest in the link between the composition of the atmosphere and global temperature is nothing new: In 1784 Benjamin Franklin suggested that the hard winter of 1783-84 was due to the presence of excessive dust in the atmosphere. Early in the 19th century, Jean Baptiste Joseph Fourier announced that the atmosphere acts like the glass of a greenhouse, impeding the escape of the earth's radiation to space. Svante Arrhenius was the first however to recognise the role of certain key atmospheric components when, in 1896, he estimated that the presence of water vapour and CO_2 in the atmosphere makes the earth 33 °C warmer than it would otherwise be (Kaye 1990). He also estimated that a doubling of CO_2 would produce a rise in global temperature of 5-6 °C.

Of more recent interest is the way in which the composition of the atmosphere has been altered by man and what the consequences of this tampering could be. Since the Industrial Revolution (circa 1700) globally averaged atmospheric concentrations of CO_2 have increased by the order of 30% (Pearman 1988). This combined with the addition of other "Greenhouse Gases" (for example CH_4, CFC's), has resulted in an increase of the total "Greenhouse Forcing" in the atmosphere. Measured over the period 1850 to 1990, over 50% of the additional forcing has been added to the atmosphere in the last 30 years (Hansen et al. 1989). It would appear therefore that the rate of forcing is accelerating.

Concrete proof that increased concentrations of anthropogenic Greenhouse Gases in the atmosphere are actually causing global warming is, as yet, unavailable, but over the last century globally averaged air temperatures have shown an apparent rise of more than 0.5°C (Jones et al. 1986, Wigley et al. 1986, Hansen & Lebedeff 1988, Kerr 1990). In addition, other indicators which would be expected to accompany global warming such as thinning of Arctic Ice (Wadhams 1990), increased ocean upwelling (Bakun 1990) and global sea level rise (IPCC 1990a) are becoming apparent and all lend credence to the suggestion that the "Greenhouse Effect" has arrived.

Modelling of the Greenhouse Effect predicts further increases in global temperature and subsequent global sea level rise due to glacial wastage and thermal expansion of the oceans. As a result of the accelerating Greenhouse Forcing in the last few decades, rates of temperature increase and sea level rise are also likely to accelerate. Some rise in sea level as a result of Greenhouse Forcing already present in the atmosphere is inevitable (Rahmstorf 1990) and predictions of over 1 m rise before the year 2100 have been made (Thomas 1987). A rise of this magnitude would obviously have serious inundative and erosional consequences for many low lying countries. Estimates of losses such as 9% of the population and 11.5% of land available in Bangladesh, the whole of New Orleans city and large portions of the Netherlands and the Nile Delta, not to mention numerous Indian and Pacific Ocean islands, have been frequently referred to by the popular media. Titles such as "....How Americans Could Abandon An Area the Size of Massachusetts" (Titus 1990) do not immediately instill confidence in the future, but emphasise the necessity of effective coastal management in order to reduce the impacts of sea level rise.

Measurements from a global network of tide gauges indicate a rise in global sea level of between 10 cm and 15 cm has occurred over the last century and rates of sea level rise around South Africa have been found to be comparable (Hughes et al. 1991a). This amount of rise is less than that predicted from modelling of the forcing already in the atmosphere although thermal lags in the atmosphere and oceans may be responsible for this reduction. On the basis of the agreement between South African and global historical sea level trends, it is reasonable to accept the globally modelled predictions of sea level rise as being applicable to South Africa. Sea levels, therefore, may be expected to rise within the designed lifespan of existing infrastructure and development in this country, to levels above the design criteria for much of that development. Rising sea levels will result in a loss of land through erosion or flooding and inundation of low lying sections of the coastline. Saline intrusions will move further inland increasing salinities in soils, aquifers and estuaries and raised water tables may cause engineering problems for certain constructions. In addition an increase in storm damage to coastal development and infrastructure may be anticipated.

Sea level rise will have different effects along various portions of the world's coastlines depending on conditions such as sediment type and coastal planform. In impact assessment, it is necessary to divide the coast into physiographic regions for consideration of their response to relative sea level rise. For example, the conditions in Louisiana do not apply to the coast of Maine because the Mississippi delta region is very flat and undergoing pronounced compaction and subsidence, while northern New England is characterised by non-erodible cliffs and portions are experiencing neotectonic uplift (National Research Council 1987). Likewise, the vulnerability of the high cliffs of South Africa's Cape Peninsula is much lower than many of Cape Town's sandy-shored Atlantic coast suburbs. Soft erodible coastlines backed by flat and low lying coastal plains are obviously the most vulnerable to relative sea level rise. These type of environments are generally estuaries, tidal inlets, deltas and barrier islands which comprise a significant portion world's coastline. In Australia alone, 70,000 km^2 of low gradient tidal flats, coastal wetlands and chernier-beach ridge plains are vulnerable to sea level rise (Short 1988). The aesthetic appeal of these environments - often a result of their impressive productivity and bio-diversity - and their suitability for construction combined with other more direct economic factors often facilitate considerable development in them. This development pressure is expected to increase significantly; 60 % of the world's 5.3 billion people live within 60 km of the coast and within the next 20 - 30 years this portion is expected to double. Adding the population pressure variable to sea level rise often means that shorelines (and ecosystems) do not have room to migrate landward. Factors such as local sediment dynamics may become more important and additional pressure is put onto freshwater supplies and other infrastructural requirements of coastal settlements (e.g. Leatherman 1991, 1986, EPA 1985, Lee 1991, Pernetta 1991). Despite difficulties in modelling these impacts, these low gradient, often highly populated environments are clearly at risk and should be awarded the highest priority in the assessment of their vulnerability.

In some instances it is possible to put a value to the development and infrastructure at risk, but in order to do this a sound inventory of property at risk and hazard database must be available. Usually it is only First World nations that have this type of data available. However, comparisons with First World studies may be drawn and it is instructive to learn of the order of magnitude of cost involved. Yohe (1990) using a sample of 30 discrete units along the U.S. coast estimate the cost of <u>not</u> protecting existing development at risk for sea level rise scenarios of 0.5 m and 1.0 m. His calculations show that existing development to the values of U.S. $ 39.2 billion and $ 65.6 billion will be in jeopardy by 2050 and $ 133.3 billion and $ 308.7 billion by 2100. Titus et al. (1991) on the other hand, estimate the cost of: (1) protecting ocean resort communities by pumping sand onto beaches and gradually raising barrier islands in place; (2) protecting developed areas along sheltered waters through the use of levees and bulkheads; and (3) loss of coastal wetland and undeveloped land from a 1 m rise in the U.S. to be between \$ 270 and \$ 470 billion, ignoring future development. If no protective measures are taken 30,000 km^2 of land would be lost and 1,500 km^2 of densely developed coastal lowlands could be protected for \$ 1,000 - \$ 2,000 p.a. for a typical size plot. Considering the value of much of this real estate they consider protection to be justifiable. Either way, the cost of sea level rise to U.S. property would appear to be significant, let alone the cost of possible reductions in ecosystems and bio-diversity.

South Africa does not have any well developed deltas or barrier islands but much of the coastline consists of soft or erodible sandy shores, backed in many places by coastal lowlands, vleis and wetlands. Unlike the Dutch, who have had an excellent coastal monitoring program in place since 1843 and updated in 1965 to evaluate shoreline movements (Hoekstra and Stolk 1990), the South Africa coastline is without any long-term monitoring. Most of the coast is currently eroding and therefore under threat, save for a few isolated areas of progradation (Tinley 1985). It is uncertain what the current effects of relative sea level changes are on the coast but these effects will probably be exacerbated by future sea levels.

In addition, South Africa has a rapidly expanding population and demand for housing, much of which is centered around coastal inlets and estuaries - areas which in many cases are considered environmentally sensitive. Many of these settlements are informal with no planning control and one of the major worries is that today's informal camps are forming the basis of tomorrow's new and formal towns. This pressure and demand, coupled with a lack of foresight, may result in the degradation of future coastal developments. Figure 1 shows the coastal population densities of the world from which it is clear that most of South Africa has population densities equal to much of Europe and even greater than parts of the west coast of U.S.A.. Sea level rise is not simply a First World problem and due cognisance must therefore be given to it in South Africa early on in the coastal structure planning stage. Considering the recent political changes in this country and the greater public awareness of its "Green Heritage," planning decisions on this level must surely be of the utmost importance to the "New" and developing South Africa.

Many countries with coastal boundaries such as Australia, The Netherlands and some U.S. States are already taking a proactive role or at very least, have legislation in place which is readily adaptable to sea level rise planning. In addition, government funding is being directed towards sea level rise, coastal monitoring and impact assessment studies to improve on the existing models and procedures. Many of these studies correlate long historical data records of shore movements and relative sea levels (e.g. EPA 1985, Leatherman 1984). Unfortunately South Africa does not have long sets of historical shoreline change data which may be of use in sea level rise planning and indeed coastal management is a relatively new practice in this country. However guidelines for coastal land use, within a framework of Integrated Environmental Management, have been suggested (IEM 1989) and are beginning to be implemented by coastal planners (Schneier, Dept. Env. Affairs. *pers com* 1991). The incorporation of a "planning for sea level rise" philosophy into these recently conceived guidelines is essential and is a practical and relatively easy step to take, even in the absence of long term data. Such a proactive management approach is required to ensure the continued existence of an aesthetically pleasing and ecologically sound coastline, adjacent to the major population centres, yet suitable for recreational purposes. An assessment of the nation's vulnerability to sea level rise must therefore be made.

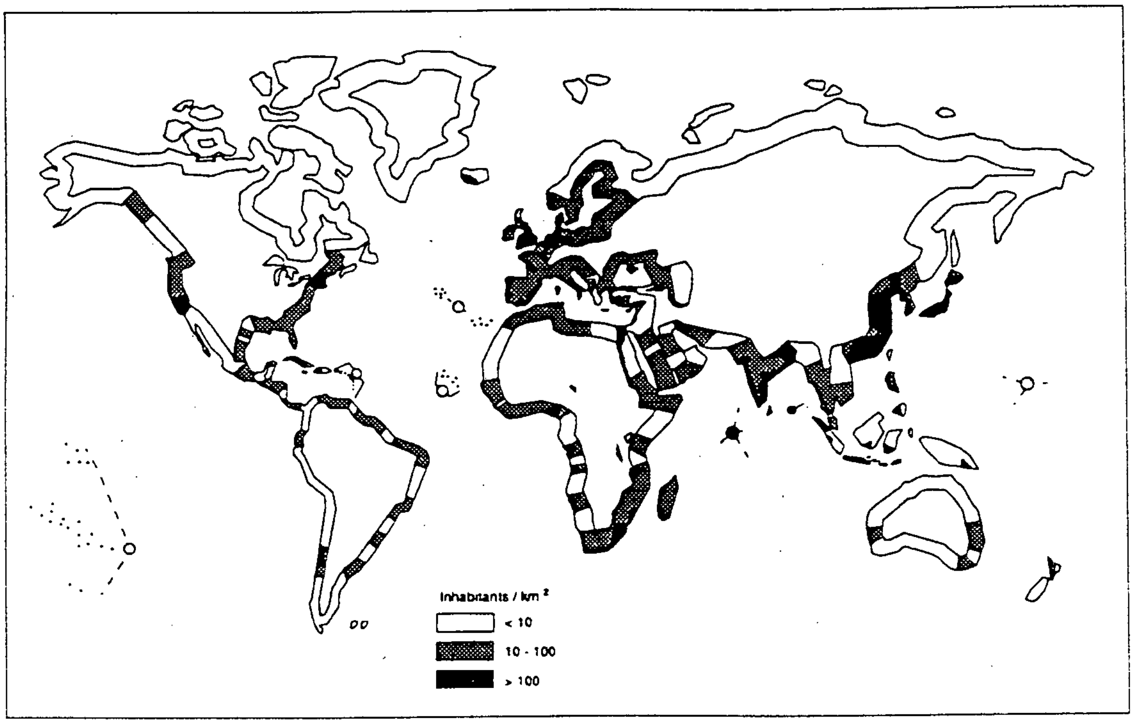


FIGURE 1. World coastal population densities (after Holligan 1991).

A common methodology for the assessment of vulnerability to sea level rise has been put forward (IPCC 1991). The methodology follows seven steps to the development of a coastal management strategy:

1. Delineation of case study area and specification of accelerated sea level rise boundary conditions.
2. Inventory of case study characteristics.
3. Identification of relevant development factors.
4. Assessment of physical changes and natural system responses.
5. Formulation of response strategies and assessment of their cost and effects.
6. The assessment of the vulnerability profile and interpretation of the results.
7. Identification of actions to develop a long term coastal zone management strategy.

Within South Africa much of the background data required, especially for steps 2 and 3, are either; unknown, or known only with sufficient accuracy to be potentially misleading, or involve investigation and assimilation beyond the scope of a single project. In the absence of data for shoreline changes, population pressures and even such factors as established land valuations, a more qualitative approach must be taken. The approach necessary must be adaptive, bearing in mind the data available, and comparative. Such an approach considers a series of assessments carried out on a scale which uses the information available and then compared on a broader, less defined scale providing a base-line study on which to ground future more detailed impact assessments.

This thesis is intended to provide such a first step in identifying and managing the impacts of sea level rise on the South African coastal environment. It evaluates the possible impacts and identifies those areas and infrastructure most vulnerable to those most serious hazards. It further suggests the application of suitable management procedures. An understanding of the key processes involved is developed using a case study approach in locations taken to be representative of environments found around the South African coast. Having determined the likely responses of a set of "type localities", the responses are applied on a regional scale and a regional impact assessment is built up. The regional impact assessment is then extended along the whole South African coastline. Where possible, management options are discussed.

Having stated the objectives and terms of reference, an overview of the structure of this thesis may be given:-

Chapter 2 provides a brief literature review of historical global atmospheric and climatological changes and their predicted effects on the future. Comparisons with South African trends are made and in doing so a scenario for future sea level rise in South Africa is developed. The relevance of sea level rise studies in South Africa and the importance of planning for the rise is considered.

Chapter 3 discusses the general categories of impacts of sea level rise and describes the approach, rationale and methodology used to model these impacts, both on a localized/case study and on a regional basis.

Chapter 4 presents detailed case studies of the impacts of sea level rise on four different types of environments which are taken to be representative of the South African coast. Where possible, management options are discussed in context and the key processes governing the impacts of sea level rise on the South African coast are identified.

Chapter 5 draws on the conclusions of the case studies to develop a Coastal Vulnerability Index (CVI) which provides a simple first order estimate of the "economic" impacts of sea level rise on a regional basis. The CVI is applied to the two geomorphologically contrasting but comparably populated regions - the Cape south coast and Natal south coast. The suitability of the CVI for the whole coast is considered.

Chapter 6 forms the main discursive section of the thesis and observations from the case studies and applications of the CVI are discussed. The findings from the CVI are extended across the whole coast and the vulnerability of the South African coastal environment to sea level rise is summarized. The management options are presented in the form of a literature review and the international approach towards the effects of sea level rise is presented. The local perspective is considered, the likely problems summarised and suggestions for effective management using existing coastal management legislation are made.

Chapter 2

THE SOUTH AFRICAN PERSPECTIVE OF GLOBAL CHANGE

2.1 Is there any cause for concern?

Recent studies of global warming have shown that, since 1856, global mean temperature has apparently risen by 0.5°C (Kerr 1990) and that the six hottest years on record have all been in the 1980's in (decreasing) order, 1988, 1987, 1983, 1981, 1980 and 1986. Although 1989 was anticipated to be much cooler (Pearce 1989) (as a result of the onset of a cool phase of the El Nino phenomena in the eastern Pacific since mid-1988) it too has been reported to be one of the warmest years on record (Kerr 1990). Further evidence for the robust continuation of the recent warming trend came from claims made late in 1990 that the first eight months of 1990 "should easily make it the warmest year yet recorded" (GECR 1990)). In fact Jim Hansen, the director of NASA's Goddard Institute For Space Studies, went so far as to take an open bet that one of the first three years in the 1990's would prove to be the hottest on record. Subsequently 1990 proved to be 0.45°C hotter than the 1951-80 average and the hottest year on record on three long-term sets of observations (Kerr 1991) with 1991 being second warmest in the past 140 years (GECR 1992).

There has been considerable skepticism in the popular and scientific press as to the validity of this apparent warming (e.g. Lindzen 1990) with explanations such as urban heat island effects, station spacing bias and "natural longer-term cycles" being put forward. However, the likelihood of such an arrangement being simply a manifestation of the natural variability of the system is low - probability between 0.010 and 0.032 (Tsonis and Elsner 1989) and although not yet proven, there is a strong suspicion that the observed global warming is a realization of the Greenhouse Effect. Two phases of rapid warming are apparent (Jones et al. 1986, Hansen and Lebedeff 1988); one between the 1880's and 1940's, and the other from the mid-1960's to the present (Fig. 2). The former appears to be more evident in the northern hemisphere while the latter appears more global in nature.

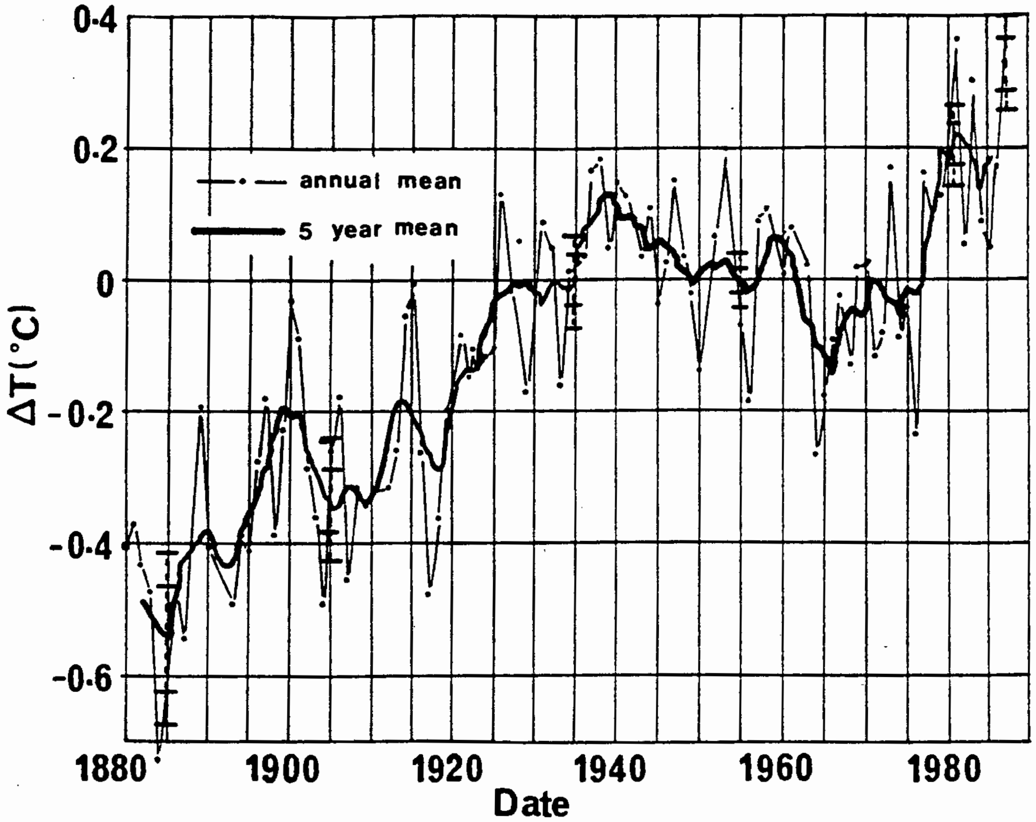


FIGURE 2. Global surface air temperature. The 5 year mean is the average of the 5 years centered on the plotted year. Uncertainty bars represent 95% confidence limits (after Hansen and Lebedeff, 1988).

Examining the forcing behind this "anthropogenic" warming it would appear that since the Industrial Revolution (CIRCA 1700), atmospheric concentrations of carbon dioxide have increased substantially and appear to be accelerating. For example pre-Industrial atmospheric levels measured from ice cores, indicate a value of 275 $\pm$ 10 ppmv (Pearman 1988) and measurements taken in Hawaii show an increase from 1958 levels of 315 ppmv to 1989 levels of 353 ppmv (White 1990). Modern levels therefore represent a 28 % increase in the 300 years since pre-Industrial times, 12 % of which has occurred over the last 31 years. If the Greenhouse Theory is correct, then global temperatures will continue to increase as a result of concentrations of Greenhouse gases already in the atmosphere and will probably accelerate with continued increases in Greenhouse emissions.

The next question to be addressed in the global change scenario is - **how and to what extent does global warming affect sea level?** The concept of global sea level is based on the analysis of tide gauge records from around the world's coastlines. Tide gauges record the changes in sea level relative to land, i.e. the resultant upward and downward movement of the land margin compared with movements of the sea. Of the many processes affecting the sea level on the shoreline, the most important are changes in the ocean basin and ocean water volumes. Tectonic activity and isostasy are the dominant mechanisms for changes in ocean basin volume and although the measurable extent of these activities are generally local or at most regional in character, their total contributions are significant. Changes in ocean water volume come about by addition and subtraction of water (usually by melting or growth of ice sheets and glaciers) and by changes resulting from the thermal expansion of sea water. It is these volume changes that are important to modern society.

In order to determine any sea level trend from the tide gauge data, the tectonic and isostatic components of the gauging station must be isolated and removed. Local sediment compaction, dewatering and loading effects must also be removed and having done so, the resulting data series is taken to be representative of that station's actual sea level. Any trend in this remaining data series must therefore be a result of "another factor". Global warming will increase both the rate of addition of water to the ocean from temperate glaciers and certain ice sheets and also induce thermal expansion of the upper layers of the ocean. Global warming will therefore have an effect on global sea levels and not just local or relative sea levels. There is a trend apparent in long-term sea level data sets measured worldwide (e.g. Gornitz et al. 1982, Douglas 1991, Peltier and Tushingham 1989) and it is possible that these data are records of an intensifying eustatic sea level rise and that global warming is that "other factor" responsible for the observed trend. When fully developed, satellite altimetry and Global Positioning Systems will be able to provide a much better evaluation of trends in sea level versus land movements. However, these methods are not currently practicable and traditional surveying methods and more and longer tide gauge records must be relied on to prove the existence of this apparent global trend. Many low lying coastal communities worldwide are vulnerable to changes in sea level and it is imperative therefore to determine its magnitude and rate of rise as soon as possible in order to plan for the impending changes.

Ample discussion of the methods of deriving global sea level trends and their contentions have been given elsewhere (e.g. IPCC 1990, Hughes et al. 1991a, Morgan et al. 1991, Wyrtki 1990, Douglas 1991, EPA 1983) and it is not intended to further develop their arguments in this thesis. However, the consensus of scientific opinion is important:
Table 1 shows the range of estimates of historical mean "global" sea level increases to date. In 1990, the peer reviewed assessment of the Working Group 1 for the Intergovernmental Panel for Climate Change (IPCC) provided the most holistic statement on sea level rise to date and judged that:-

1. "global sea level has been rising."

2. "the average rate of rise over the last 100 years has been 1.0 - 2.0 mm/yr."

3. "there is no firm evidence of an acceleration in global Mean Sea Level (MSL) rise over this century (although there is some evidence that sea level rose faster in this century compared to the previous two centuries)."

Although this may be considered a fairly "safe" summary even this continued rate of rise would be sufficient to cause deleterious impacts on many of the world's coastlines.

After obtaining a global trend in sea level, Gornitz et al. (1982) compared their curve with a previously obtained global temperature curve. On the basis of a linear relationship they recognised an 18 year time lag between temperature and sea level response which they attributed to the thermal relaxation time for the upper layers of the ocean. (This lent support for the concept of thermal expansion of the oceans being partially responsible for the rise. Support for a lag of this order of magnitude is given in Rahmstorf's model for the ocean's response to climatic change (*in press*).) If the observed global rise in sea level <u>is</u> a result of the observed global temperature increase, this suggests that the current rate of sea level rise is reflecting the apparent warming of the early 1970's and the sea level rise resulting from the rapid temperature increase to the 1980's values has yet to be realised. A conceptual study of possible future tide gauge data has shown that the MSL acceleration anticipated from the global warming should be apparent in the records by the early part of the next century (Woodworth 1990).

TABLE 1 Estimates of mean "Global" sea level increases (updated after Pearman 1988).

AUTHOR	**RATE** (cm/century)	**PERIOD**
Thorarisson (1940)	> 5	
Gutenberg (1941)	11 ± 8	-1937
Kuenen (1950)	12 - 14	-1942
Lisitzin (1958)	11.2 ± 3.6	6 stations
Fairbridge & Krebs (1962)	12	1900-1950
Emery (1980)	30	1935-1975
Gornitz et al. (1982)	12	1880-1980
Klige (1982)	15	1900-1975
Barnett (1984)	14.3 ± 1.4	1881-1980
Barnett (1984)	22.7 ± 2.3	1930-1980
Peltier et al. (1989)	24.0 ± 9.0	1920-1970
Wahr et al. (in press)	16.7 ± 3.3	1900-1986
Douglas (in press)	18.0 ± 1.0	1880-1960

So how do South African sea level trends compare with global sea level rise? Tide gauge records in South Africa are generally short in comparison with other records worldwide and are often incomplete. The South African coastline, and in particular the west coast, is thought to be of reasonable tectonic stability with little or no local movements and should therefore be able to provide a good reflection of long term trends in sea level (Hughes et al. 1991a, Marker 1984). In addition, by virtue of its position in the southern hemisphere, which contains some 70% of the world's oceans, any sea level information will be exceedingly relevant to the determination of global trends. Figure 3 shows the spacing of the South African tide gauge network which is adequate to provide a reasonable national coverage.

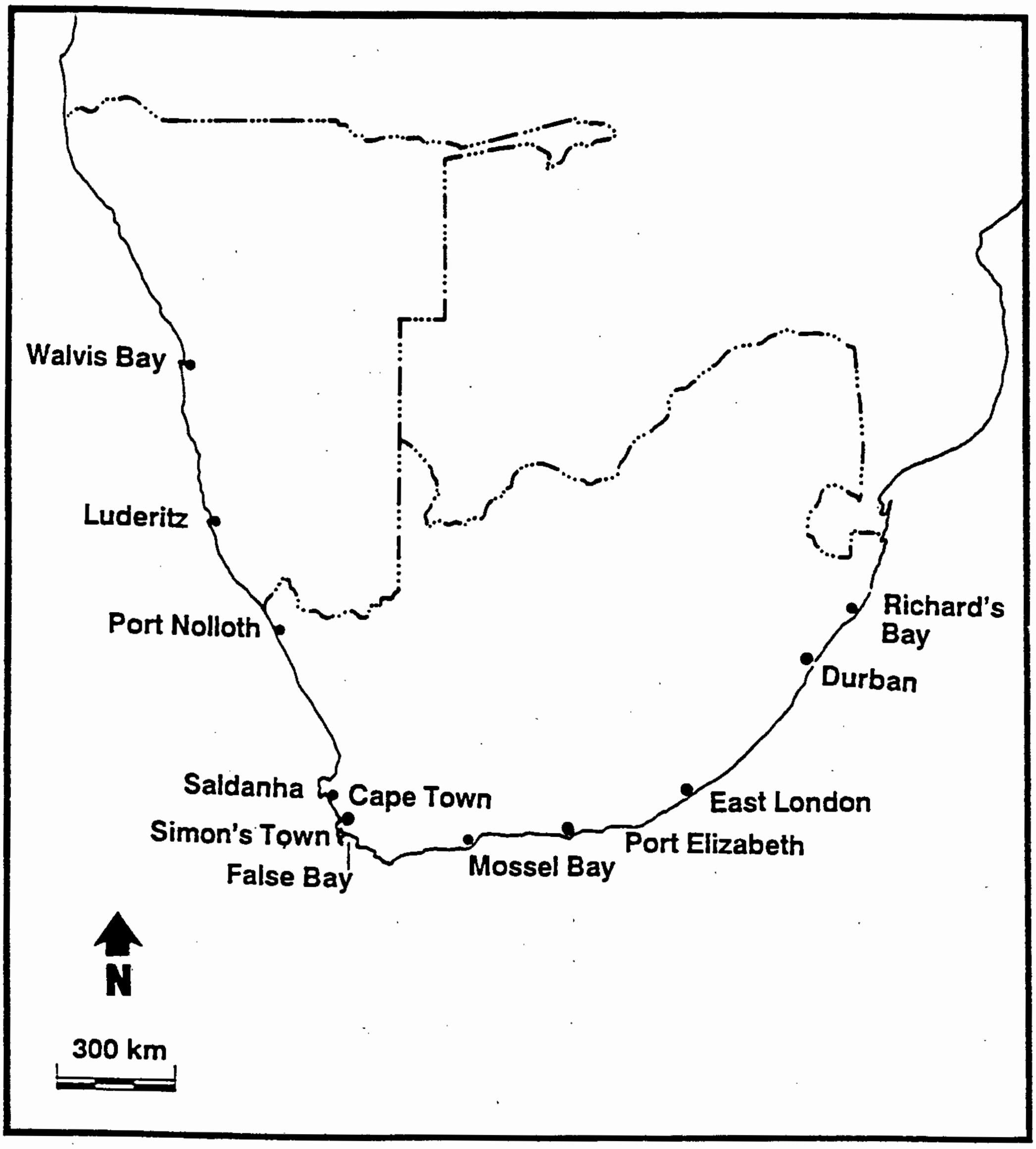


FIGURE 3. The South African tide gauge network.

Of the four long records of mean sea level for South Africa, three show a positive trend of increasing sea level over the post-analysis period 1961-1987 (Hughes et al. 1991a). The trend at Port Nolloth shows an increase in relative sea level at the 95 % confidence level of 12.3 mm/decade with standard error of 3.7 mm/decade (Fig. 4.). The Simon's Town and Luderitz trends are similar and approach this level of confidence but the Mossel Bay record shows no determinable trend. Clearly the South African trends compare favourably with the global estimates of sea level rise (Table 1). Peltier and Tushingham (1989) showed that secular relative sea level trends around southern Africa are significantly contaminated by ongoing glacial isostatic adjustment. If this contribution (+15 mm/decade near Port Nolloth) is removed from the signal, the combination of relative sea level rise and isostasy indicates a eustatic rise measured at Port Nolloth of approximately 27 mm/decade over the period 1961-1987. This is still in keeping with the estimates of global sea level rise (Table 1), especially those measured over a shorter and more recent period, and could possibly lend support to the suggestion in those estimates of an accelerating rate of sea level rise. Such an acceleration would be expected in the light of increasing Greenhouse forcing.

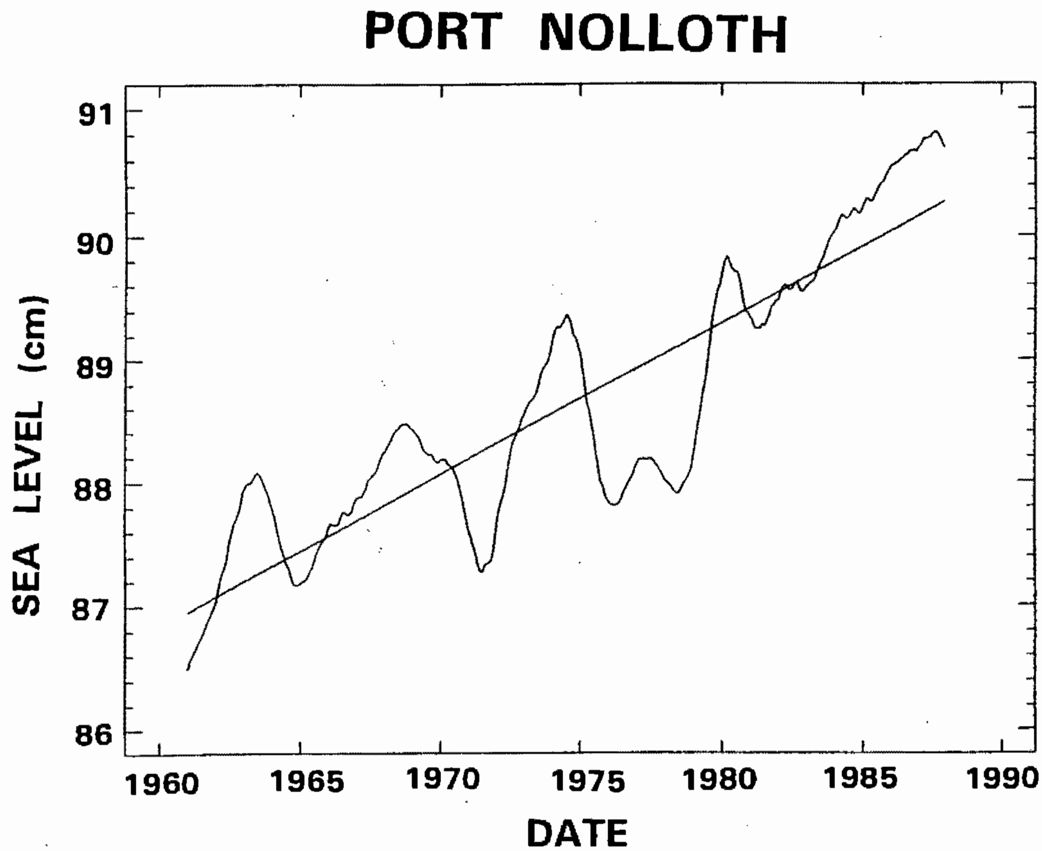


FIGURE. 4. The Port Nolloth long term sea level structure and linear trend of 12.3 mm/decade measured over the post-analysis period 1961-1987 (after Hughes et al. 1991a).

On the basis of the good agreement between South African and global historical trends, it is reasonable to accept that if sea level rise is a symptom of global warming then the predicted rates of globally modelled sea level rise are applicable to South Africa. The impacts of global sea level rise are therefore an increasing cause for concern for South Africa.

2.2 Predicted Sea Level Rise

A number of models for future sea level rise have been put forward over the last few years with various ranges of contribution from sea level rise "sources". The review panel of the IPCC (1990) in their "Business-as-Usual" scenario state that by "the year 2030, global mean sea level [will be] 8-29 cm higher than today, with a best estimate of 18 cm. By the year 2070, the rise [will be] 21-71 cm with a best estimate of 44 cm." They conclude that "even with substantial decreases in the emissions of major greenhouse gases, future increases in temperature and, consequently, sea level are unavoidable - a sea level rise 'commitment' - due to lags in the climate system." "...the rate of rise implied by the business-as-usual estimate is 3-6 times faster than that experienced over the last 100 years." Water "sources" for this scenario are predominantly thermal expansion of the upper layers of the oceans and additional water from melting temperate glaciers with some positive and some negative contributions from the margin of the Greenland ice sheet from Antarctica respectively. Although a wide range of estimates for sea level rise have been put forward, it is clear that even the "bottom of the range" estimates are sufficient to cause significant coastline changes.

Fig. 5 compares the global sea level rise estimates of the IPCC (1990) and the less conservative Thomas (1987). Note the similarity in response up to about 2040 after which Thomas' contribution from Greenland and Antarctica becomes more noticeable. A rise of 20 cm can be anticipated within the next 30 to 40 years, 50 cm can be reasonably expected within the next 70 to 90 years and possibly (though unlikely) 100 cm by 2100. Although the absolute certainty of future sea level rise is not yet fixed, the adoption of scenarios for planning purposes would seem pragmatic and scenarios of 50 cm and 100 cm have been recommended (e.g. Vellinga and Leatherman 1989, IPCC

1991). In this thesis, when considering the impacts of sea level rise on the South African coastal environment, the 20 cm, 50 cm and 100 cm scenarios are generally chosen for modelling purposes.

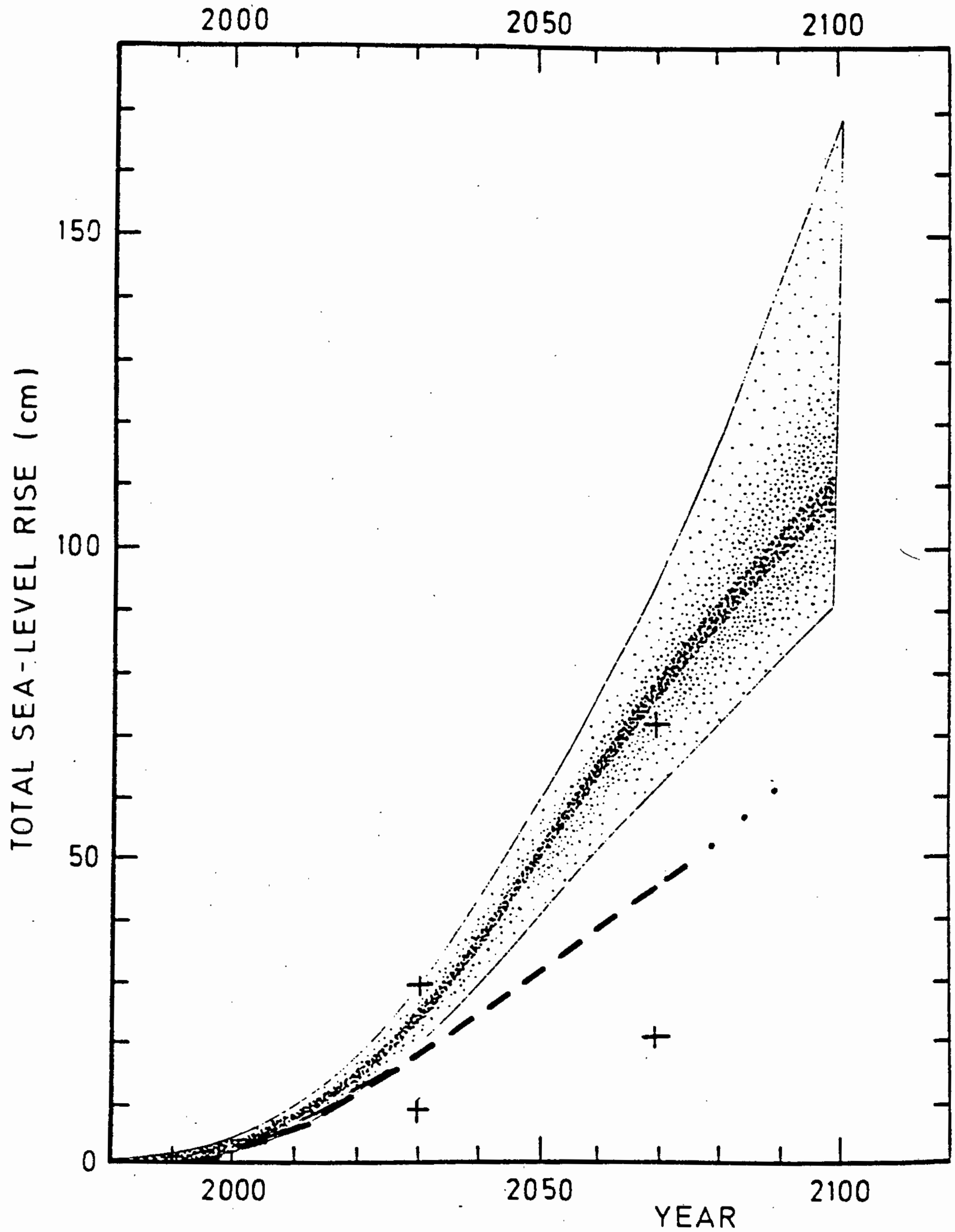


FIGURE 5. Predicted total sea level rise during the next century. The dark shading and the two thin lines indicate the most probable response and range of responses after Thomas (1987). The broken line and the crosses depict the most probable response and range of responses after IPCC (1990).

2.3 Why is global change important in the South African coastal environment?

The South African coastline extends for some 3000 km and must be regarded as an enormous national asset in terms of its aesthetic, recreational and economic value. It can be divided into four basic geomorphological regions:

THE WEST COAST: Namibia to St Helena Bay (20 km north of Saldanha (Fig. 3)). This is a dry semi-desert coastline with a low, wide and flat coastal plain cut by mostly ephemeral rivers and salt pans. The shoreline is a combination of long sandy beaches interrupted by short sections of mixed rocky and sandy bays and promontories. The long axes of small log-spiral bays point in a north-westerly direction. Conditions are extremely harsh and population densities are very low. The coast faces west-south-west to westerly.

THE SOUTH-WEST COAST: St Helena Bay to Cape Agulhas. Warm temperate climate with winter rainfall and all seasons rainfall confined to orographic highs. The coastal plain is generally wide and bounded by a combination of long open sandy beaches and rocky headlands and cliffs which often hold small pocket beaches. The coastal plain tends to narrow towards the centre of the region where cliffed sections begin to predominate. The shoreline becomes rockier southwards and rivers are usually open for at least several months of the year. Population densities range from low in the north to high, centred around the Greater Cape Town area which extends east past False Bay.

THE SOUTH COAST: Cape Agulhas to Cape Padrone (50 km east of Port Elizabeth (Fig. 3)). Mixed rocky coastline with pocket beaches becoming sandier towards the east where large log-spiral bays become characteristic, pointing towards the north-east. The wide, flat and low coastal plain narrows towards the east and is cut by tidal inlets and estuaries with tidal reaches extending several tens of kilometres inland. Warm temperate climate, generally with all seasons rainfall and medium to high population densities in coastal towns, cities and resorts.

THE EAST COAST: Cape Padrone to Mozambique. Linear trending monoclinal coastline with irregular, indented rocky section separated by linear or arcuate beaches, often coarse grained. The coastal plain is very narrow towards the south and rivers are deeply incised forming drowned river mouths rather than estuaries. North of Durban (Fig. 3) the coastal plain

starts to widen again and the rivers become less deeply incised with wider floodplains. Barrier dunes are formed towards the north. The climate is subtropical with mostly unimodal summer rains. Population densities along this coast are medium, but high within 150 km north and south of Durban, decreasing northwards to low and very low near the Mozambique border.
South Africa has a large wave climate as can be seen from the design wave conditions shown in Figure 6. A 0.1 % exceedance approximates to a 1 : 1 year wave and 0.01 % exceedance, a 1 : 10 year wave. Although a direct comparison of South African wave heights with other wave climates world-wide has never been carried out, a useful simile may be made to indicate the severity of this wave climate. A comparison of the 50 % and 0.1 % exceedance values (CSIR 1984) for South Africa with annual mean values of significant wave heights (Carter and Draper 1988) and largest observed wave heights measured in one year (1970) off Land's End, England (Neu 1976) show strong similarity. Maximum wave heights around Land's End are among the largest in the north Atlantic, almost twice as large as those off eastern U.S.A. and more than twice as large as those off Florida (Neu 1976). By analogy South Africa has a robust wave climate although the maximums may not be as large as some of those attained during storms in the North Sea (Rossouw, Univ. Stellenbosch, *Pers. Comm.* 1992). Waves along the west coast are predominantly southerly and along the south-west and south coasts are mostly from the south-west. Along the east coast, wave directions are influenced by tropical cyclones and have a north-easterly component so that they are bi-modally distributed south south-west / north-east (Rossouw 1989).

More than 80 % of the shoreline is made up of mobile sandy beaches and dunefields which are highly sensitive to interference. Whilst much of the remainder consists of rocky shores, which on the outset would appear less vulnerable, there are also the estuaries, lagoons and coastal wetlands so attractive to developers, but which are generally those coastal resources most sensitive to disturbance. Population pressure on the coast is increasing rapidly and development is being carried out, either in ignorance or arrogant defiance of the problem. Coastal management is a relatively new practice in South Africa and unscrupulous developers have avoided their responsibilities sometimes with potentially dangerous consequences*. Legislation and guidelines are necessary to counter any further degradation of the coastal environment and protect unaware land owners and purchasers#.

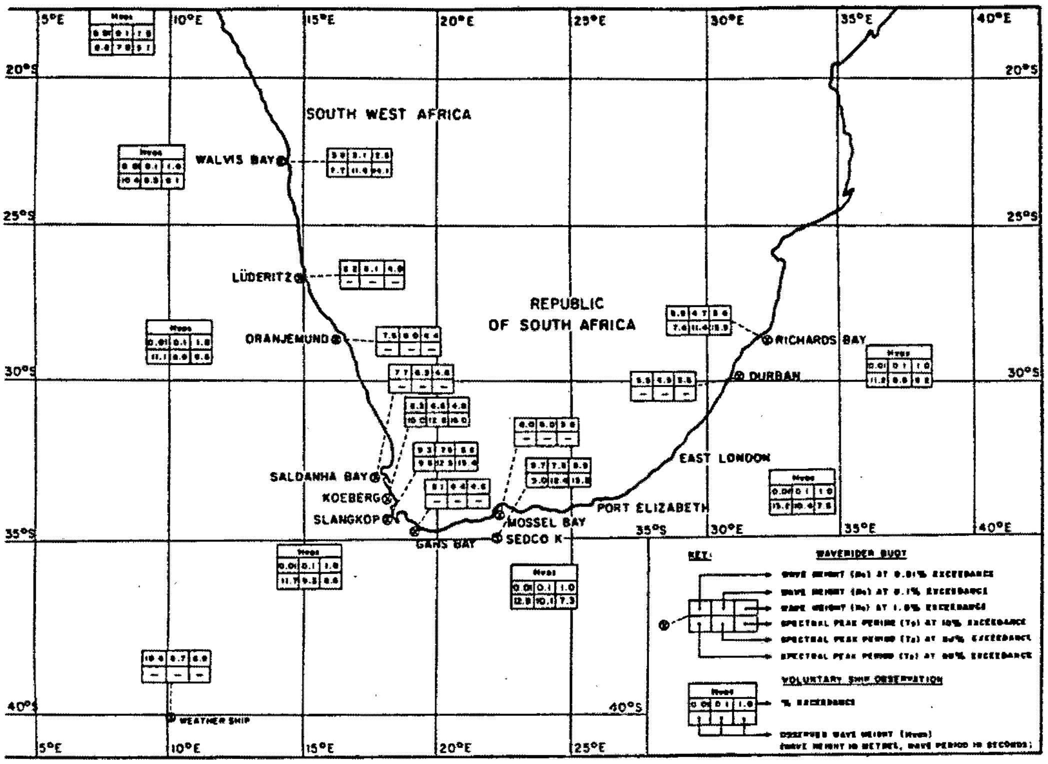


FIGURE 6. Design wave conditions for South Africa (after CSIR 1984).

As the sea level rises the shoreline will undergo a number of transformations which will include erosion, flooding and saline intrusion and in some cases these may be perceived as degradations. The magnitude of these effects and the complexities of their inter-relations will depend on factors such as whether the shore is exposed to the open ocean or sheltered in a bay, the

* For example, in Bayview, an upmarket northern suburb of Mossel Bay, development has been carried out to the edge of the high semi-consolidated dunes. The seaward face of these dunes is currently being eroded and sections of recently laid lawned garden from uncompleted houses have slumped to the beach some 20-25 m below. Even with current rates of coastal erosion let alone the predicted increased rates of coastal erosion, the posterity and investment potential of this development is questionable.

\# The impacts of sea level rise and the future vulnerability of property is currently being considered for inclusion in insurance ratings (Pers Comm. P. Evans, Chairman Insurers' Special Perils Committee, Commercial Union Ins. Co., Dec. 1991.)

effect of any stabilizing structures and population densities and activities. An understanding of the potential impacts of sea level rise is therefore essential for effective future management of the South African coastline. Chapter 3 provides an account of the likely impacts of sea level rise. These impacts will affect the entire coastline and although the ecological consequences of sea level rise are not discussed in any detail, these must never-the-less be considered at all management legislative and guideline stages.

In addition to sea level rise, there are a number of other symptoms of global climate change which may also have a negative impact on the coastline. For example, increased aridity associated with the global warming (especially on the south and south west Cape coasts) may tend to reduce the efficacy of dune colonizing plants. As a result, dunes that were once well vegetated and stable may become poorly vegetated and more mobile, thereby exacerbating coastal erosion problems. Likewise, changes to the rainfall regime (and therefore river flow) may affect sediment supply to sections of the coast. Unfortunately changes in South Africa's coastal climatology are not yet reliably predictable and it is not yet possible to accurately delineate potentially arid areas. Another symptom of global warming around South Africa may be an increase in the occurrence of storms of tropical cyclone intensity. Changes in sea surface temperatures, which indicate a certain measure of tropical cyclone stability, appear to be following an upward trend and as a result, future storm characteristics for the east coast may be suggested:-

The average minimum sea surface temperature (SST) required for stability of tropical cyclones in the southern Indian Ocean is 26.5°C. Shannon and Taunton-Clark (1988) have provided SST data for the Agulhas Bank coastal area over the period 1906 to 1986 and manipulation of this data reveals a linear increase of 0.16°C/decade (Brundrit et al. 1989). This trend is in keeping with other trends for southern Africa (Folland et al. 1984). If this rate of increase is applied to the February mean SST isotherms for the southern Indian Ocean (La Violette and Mason 1967) then by the turn of the next century the 26.5°C boundary isotherm will be positioned approximately off Port Elizabeth. This is not to say that by 2100 tropical cyclones will be battering on the shores of Port Elizabeth, but rather this indicates that severe storms, possibly of tropical cyclone intensity, could become more frequent on the Natal coast over the next century.

CHAPTER 3

IDENTIFYING IMPACTS OF SEA LEVEL RISE: METHODS

3.1 Modelling

The beach and nearshore is the region where the forces of the sea react against the land. It is where the land responds to this attack with a variety of "give and take" measures which alter the shape of the profile to dissipate the sea's energy in the most efficient manner. For a given beach, the slope is dependent on the particle size of the beach material, the period and height of the waves. The gradient will tend to decrease with increasing wave height and period, giving a dynamic balance with storms tending to move material offshore and gentler swells pushing material back onshore. Consequently the shoreline is an exceedingly dynamic environment and changes in sea level and sediment availability are probably the major factors determining the evolution of the coast. Changes in sediment flux can be influenced by human activity and therefore relatively easy to manage or to disrupt. Changes in sea level, on the other hand, are not easily managed and each morphological unit responds in a particular way according to its resistance to change and the rate of sea level rise. It is difficult, therefore, to reduce the coastal evolution problem to one of simple statements but for the purpose of a first evaluation of impacts or vulnerability to sea level rise, it becomes necessary.

When considering the processes invoking changes to a shoreline, the impacts of sea level rise may be generalised into four main categories;-

1. Increased coastal erosion.
2. Increased inundation.
3. Increased salt water intrusion and elevated coastal groundwater tables.
4. Reduced protection from storm and flood events.

Although impact categories 1 and 2 both result in the same consequence - i.e. the loss of land, either temporarily or permanently, their processes differ. For the purposes of modelling, it is essential to examine the processes which may give rise to a consequence or outcome of such action, - hence the four-way categorization.

The processes and mechanisms involved in these effects are site specific and vary in their intensity from location to location. It is necessary therefore to assess a locations' vulnerability in the light of;-

1. Geology, sedimentology and hydrology.
2. Attitude or exposure to wind, waves, currents and general climatology.
3. Offshore bathymetry and coastal topography.

A considerable volume of literature has been published in recent years relating to the impacts of sea level rise and methods for modelling such impacts. Although much of the work was formative in the development of this assessment strategy and choice of modelling method, it is not the intention of this thesis to provide a detailed review. As a result, a representative sample of texts are included rather than a full review and it is recommended that anyone setting out on a similar task such as this assessment, acquaint themselves fully with as many studies as possible before commencing their own:- Komar et al. (1991), Mehta and Cushman (1988), National Research Council (1987), Frassetto (1991), Bruun and Jacobsen (1990), EPA (1985), Leatherman (1984), Dean and Maurmeyer (1983), Hands (1983). One feature that stands out in these studies is their use of historical records of shoreline changes and their correlation with relative sea level changes at those sites. Unfortunately historical rates of change of the South African shoreline are largely unknown and even relative sea level records are either short or incomplete for most of the coast. Aerial photographs of sections of the coast dating back several decades do exist but their evaluation for shoreline changes is hampered in most cases by a lack of fixed reference points on the ground due to the sporadic and often haphazard nature of this country's coastal development. Their interpretation is therefore beyond the scope of this project.

The modelling of the above mentioned impacts and the model suitability in a South African context will now be discussed: All modelling assumes the continuation of present atmospheric and wave climates. Likewise changes in currents and wave refraction resulting from changes in water depth (which may become responsible for shifts in such features as the axes of log-spiral bays) are not considered.

3.1:1 Beach erosion

As sea level rises so the zone of active processes is raised relative to the land surface. Three models for the shore-normal effects of sea level rise have been proposed (Fig. 7) (Carter 1988). In these models an equilibrium profile is maintained as the shoreline is displaced landward and upward. It is usually assumed that the sediment budget is balanced and that there are no marked long-term changes in energy input. Of the three possible cases the coastal sediment may (i) erode and the products be dispersed over the shoreface below wave base, (ii) migrate onshore through mass relocation (e.g. rolling over), or (iii) remain in position as sea level rises thereby drowning *in situ*.

The first case (Fig. 7a) corresponds to the Bruun Rule (1962) and is applicable to soft mobile shorelines with no rocky outcrops. The primary assumption of the Bruun Rule is that the nearshore submarine profile will maintain a constant shape and position relative to the sea surface by translating upwards and landward as the sea level rises, balancing volumes of sediment in the cross shore direction (Fig. 8). The profile must be "soft" or erodible (usually sandy) and extends beyond the surf zone to a depth which limits shore-normal sediment transport. The basic equation is given by;

$$\text{shoreline recession (R)} = \frac{\text{profile width (L) x sea rise (a)}}{\text{profile depth (h+d)}} \qquad (1$$

where d is the limiting closure depth for the onshore-offshore exchange of material and h is the active berm height. The upwardly concave shape of this "model" Bruun Rule profile is typical of large sections of the exposed South African coast. The Rule is easy to apply, does not rely on historical data and is the preferred model and analytical technique of the SCOR Working Group 89 (Komar et al. 1991) for quantitative evaluation of the erosive response of beaches to increased water levels. Consequently it is the preferred modelling method for long-term coastal erosion used in the case studies below.

The second method (Fig. 7b) or roll-over model is an extension of the Bruun Rule and is applied to barrier island coasts where overwashing is an important process. There must, by definition, be an unfilled space behind the barrier for roll-over to be accomplished (Carter 1988). As sea level rises so material is progressively stripped from the beach and shoreface and passed over the barrier crest onto the back slope. In time landward dipping back barrier units will crop out on the seaward face. This process is particularly effective on coarse clastic barriers where there are few seaward directed transport mechanisms (Carter 1988). The basic equation is given by;

$$R = \frac{a\,(L_o + W + L_l)}{(d_o + h_o) - (d_l + h_l)} \qquad (2$$

where L_o and L_l represent the widths of the active profiles on the ocean and lagoon sides and d_o and d_l represent limiting depths on ocean and lagoon sides. W is the barrier width and h_o and h_l represent active ocean and lagoonal berm heights.

There are no barrier islands along the South African coastline and consequently there is no occasion for the direct application of this method. However Cooper (1991), suggests that this rule may be applicable in river mouths in Natal (presumably on flood tidal deltas and low spits) and on beaches backed by a gentle bedrock slope. In the river mouth application, inadequate exposure and non-uniformity in the rock surface would make the practical determination of the bedrock slope difficult and any fluvial sediment input would slow down the migration at an unpredictable rate. Consequently this application has not yet been verified. In the beach application the overwash sediment would rest on the mainland beach. This application has potential in special cases, but its successful application has not be verified. This model is not used in the following case studies.

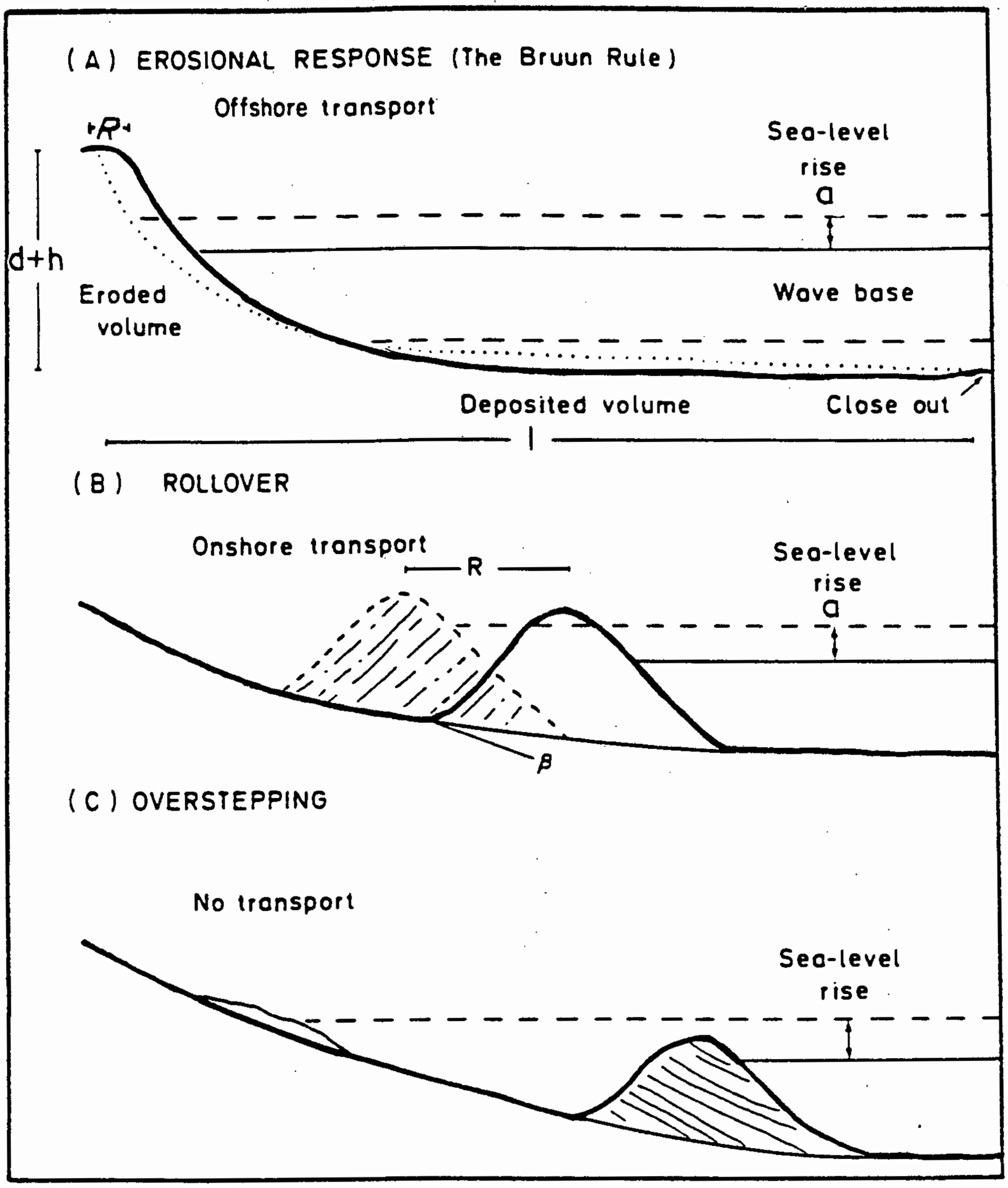


FIGURE 7. Three models of shoreline response to sea level rise. (A) The Bruun Rule, assuming offshore dispersal of eroding shoreline materials such that the rate of sea level and sea bed rise are commensurate, and the rate of erosion can predicted. (B) Barrier roll-over where a transgressive barrier recycles material as it moves landward at a rate dictated by the sea level rise. (C) Barrier over-stepping, in which the barrier is drowned and remains on the shoreface as sea level rises above it (after Carter 1988).

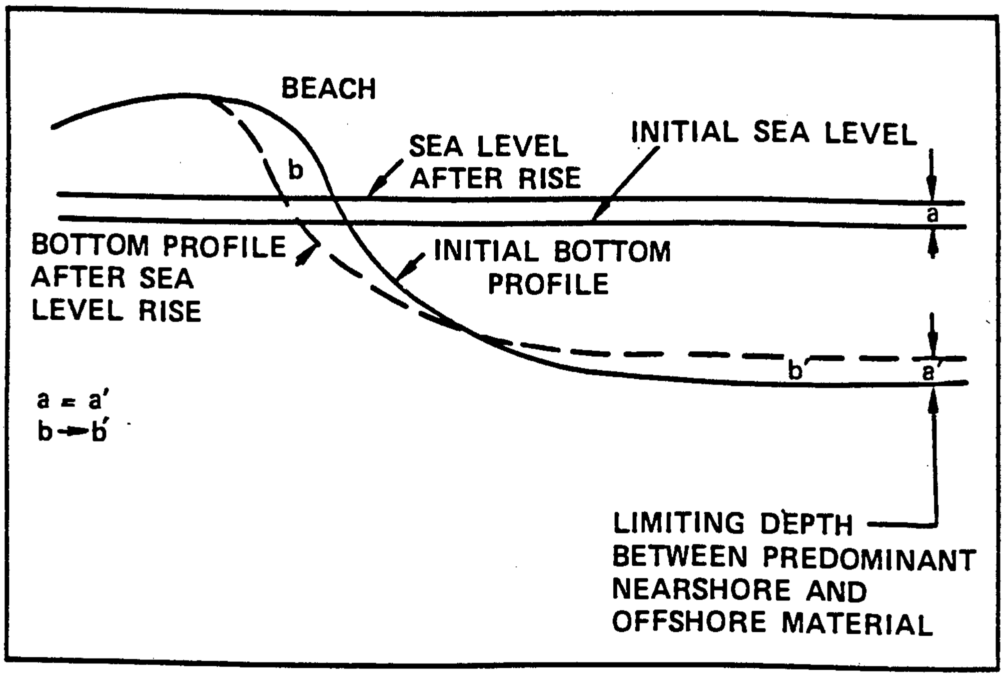


FIGURE 8. The Bruun Rule of long-term coastal erosion (after Bruun 1962).

The third model (Fig. 7c) is an extension of the roll-over model except a combination of rapid sea level rise, increased sediment influx, dynamic equilibrium in sediment transporting forces and submarine topographic features prevent the migration and rolling-over. The feature then drowns *in situ*. This response may involve a jump in the shoreline position and not a simple upwards and landward translation of the profile. The upper shore, which was originally the lagoon shore, can be expected to recede in a manner similar to that predicted by the Bruun Rule after the barrier has drowned. The modelling of the recession would be difficult without accurate predictions of over-stepping and drowning. Fortunately, there are few, if any, morphologies that are likely to drown *in situ* around the South African coastline and this model is not considered for use in the case studies.

Application of the Bruun Rule

The first and best known model relating shoreline retreat to an increase in local sea level is the Bruun Rule. Bruun (1988) provides a recent rederivation as well as a discussion of the assumptions involved in the model, its uses and misuses. Komar et al. (1991) provide the most complete discussion to date of beach response models including their theory, concepts and field and laboratory testings. Attention is drawn therefore only to those concepts which have been found to be most relevant to the application of the Bruun model in the South African context.

During the upwards and landward translation of the active profile the Bruun Rule assumes an equilibrium profile shape. Extreme (storm) events may temporarily alter this equilibrium shape but the controlling feature of the translation is some "average" profile slope, not the steeper inshore or beachface slope. This "average" slope (taken from bathymetric charts) is determined from the limiting closure depth (d) for the exchange of material between land and sea, usually taken as three to four times the maximum breaking wave height achieved in a period of between 50 to 100 years (Bruun 1988). Leatherman (1984) in a case study in Galveston Bay, Texas, found the definition of this depth to be limiting in the application of the Bruun Rule. Hallermeier (1981) provides a method, later modified by Birkemeier (1985) for a one year field trial, for assessing the closure depth by relating wave and sediment conditions to profile zonation where the closure depth approximates to 1.57 times the nearshore storm wave height that is exceeded only 12 hours/year. Considering the wave climate around South Africa this depth may therefore be conservatively estimated at somewhere between 15 m and 20 m. Komar et al. (1991) are in agreement with this methodology although they point out that although the active profile width (L) is determined by the distance offshore of the closure depth (d), its evaluation is not necessarily critical to tests of the Bruun Rule (equation 1). The "average" profile slope (ß) is relatively insensitive to inaccuracies of either L or d (which tend to be offsetting) and is taken to be representative of the average nearshore slope of the surface sediment ($\tan \beta = [d+h]/L$). The stepwise displacement of the shoreline for a sea level rise (a) may then be written as;

$$R = \frac{a}{\tan \beta} \qquad (3$$

Komar et al. (1991) referring to models of beach erosion by Kriebel and Dean (1985) and Kriebel (1990) observe that the response time scales of natural beaches may be of the order of 10 to 100 hours for storm conditions, and of the order of 1,000 to 10,000 hours for erosion induced by long term relative sea level rise. In the latter case the limit for effective shore-normal sediment transport would be far off-shore, thereby supporting the choice of an average offshore slope above the choice of a fixed limiting depth.

When considering a series of stepwise changes in water level over a long period (t), a "rate" of shoreline displacement may be considered where L, d and ß remain approximately constant. The rate of sea level rise and rate of shoreline displacement are therefore the only variables and the Bruun Rule may be written;

$$\frac{dR}{dt} = \frac{1}{\tan \beta} \times \frac{da}{dt} \qquad (4$$

However, this "rate" of shoreline recession is unlikely to be a real rate as the erosion is likely to be variable. Storms are major erosional events from which the shoreline usually recovers during calmer periods. With higher sea levels the profile will be unable to fully recover from the storm erosion back to its lower water level equilibrium position and will adopt a higher water level equilibrium position. The shore will therefore tend to recede in a stepwise manner after the occurrence storms rather than in a smooth, gradual manner.

Komar et al. (1991), Carter (1988), Dean and Maurmeyer (1983) and Bruun (1988) discuss verifications and difficulties in application of The Rule which clearly provides a good "first model". However, the consensus of the difficulties lies with the adequate definition of the dimensions and boundaries of the shore profile - i.e. the terms of reference for use. This model is two dimensional and is invariably used in a three dimensional application. It does not take into account many factors which are often observed in the South African environment that may cause changes in sediment flux and subsequent differences in profile dimensions. Typical examples of these factors are the loss of marine sediment to the land; the difference in sediment particle size and sorting between onshore and offshore which may cause offshore losses; changes in biogenic sediment production, offshore losses in currents and human interference with the rates of longshore sediment transport. However, there are a number of extensions which may be successfully applied to the

Rule (Komar et al., 1991, Bruun 1988, Dean and Maurmeyer 1983) which when used objectively within the appropriate boundary conditions, allow for a better understanding of three dimensional large scale coastal dynamics. One such extension attempts to cope with disequilibrium in longshore transport rates and considers erosion (simulating sea level rise) and deposition of sediment (reducing sea level). If Q represents the net change in sediment volume transported per metre alongshore, then the appropriate extension to the Bruun Rule is;

$$R = \frac{L\,a + \int Q\,dt}{d + h} \qquad (5$$

As for the basic Bruun Rule, over a long period (t) and with fixed Q, a gradual change in the equilibrium profile can be written;

$$\frac{dR}{dt} = \frac{1}{\tan \beta} \times \frac{da}{dt} + \frac{Q}{d + h} \qquad (6$$

This extension is used in the case studies below where there are known changes in longshore sediment transport. Where changes are insignificant, the Bruun Rule is used in its simplest form. Where changes are unknown and the shoreline appears to be relatively stable, it is assumed that Q_{input} is equal to Q_{output} and again the Bruun Rule is used in its simplest form.

Dean and Maurmeyer (1983) have made further adjustments to the rule expressing it as;

$$R = \frac{L\,a}{P(d + h)} + \frac{\int Q\,dt}{(d + h)}$$

where P is the decimal fraction of eroded material that is compatible with the surf zone sediment characteristics. Unfortunately good comparisons of grain sizes for beach and (future) borrow material are not available for the case study sites chosen. Grain size analysis of this sort is recommended for future case studies.

In more general terms, Komar et al. (1991) expresses the relationship as a complete budget of sediments;

$$P\,(d + h)\,R \;=\; L\,a + G_B$$

where the left side of the equation evaluates the quantity of littoral sediment derived from shoreline recession (R), the term (L a) is the

quantity required to maintain the equilibrium profile relative to the sea level rise (a) and (G_B) are sediment budget terms including contributions from rivers or the offshore, losses due to sediment being blown inland or transported offshore as well as the longshore gradient of the littoral drift that was included in equation (5). Expressed in this way "it becomes apparent that in predictions of the shoreline recession (R), it is extremely important to consider the (G_B) sediment budget terms in that they will commonly be large in comparison with (L a) which tends to be small due to the low rates of sea level rise" (Komar et al., 1991).
It is recommended therefore that future case studies in South Africa, requiring more than an "order of magnitude" answer, implement this complete sediment budget approach.

3.1:2 Inundation.

On an open coastline the effect of increased inundation may be modelled by adding the magnitude of sea level rise to the Mean High Water Springs tide level (MHWS) or Highest Astronomical Tide (HAT). In the absence of detailed surveyed elevations, areas adjacent to the coast which may be vulnerable to inundation are interpreted from the most detailed topographic maps available or recent aerial photography. In many cases these do not measure up to the standards required by the IPCC and thus the application is a first approximation. Inundation of open shorelines is not perceived as a major problem for South Africa. However, in sheltered environments where the effects of increased coastal erosion can be ignored, flooding and inundation may have dramatic impacts. Those sheltered environments include river mouths, estuaries, lagoons, tidal inlets and vleis, many of which are heavily developed.

With rising sea levels, a greater volume of water will be able to enter an inlet and the increase in this water volume will be related to the gradient of the inlet's banks. Steep sided inlets will have smaller increases than gently sloping inlets. As a result of the greater volume of water in the inlet, the shelter provided by the entrance could be reduced and the tidal range could change. These potential changes therefore need investigation.

The U.S. Army Corps of Engineers' Shore Protection Manual (SPM 1984) provides useful standard engineering techniques, based on empirical and mathematical models which can be adopted for this task: From a wide range of dynamically stable inlets on Atlantic, Gulf and Pacific coasts of the United States of America, Jarrett (1976, SPM. 1984a) showed a robust empirical relationship between the mid-tide cross-sectional area (A_c) of the inlet channel and the tidal prism (P) of the inlet (Fig. 9);

$$\frac{P}{A_c} \approx 10^4 \text{ m}$$

Any inlet with a soft channel which does not reach the required minimum dimensions, will use the eroding power of its high tidal flow to increase the channel size until it satisfies this stability relationship. Conversely if the channel dimensions are too large, the tidal flow will be too slow to carry all its sediment load and deposition will occur in the channel. Siltation of the channel will then occur until the correct channel dimensions are obtained (Fig. 10).

For a given channel of known dimensions King (1974, SPM 1984b) determined the maximum flow velocity in that channel (V_m) and tidal amplitude in the inlet (a_b) by considering mass and momentum balance along the channel in non-dimensional form. Applying this solution to the dimensions of a newly enlarged channel and inlet after a conjectured sea level rise, a possible new channel velocity and inlet tidal range, and hence tidal prism may be found. If the proposed tidal prism is not consistent with Jarrett's stability relationship, the channel dimensions will need to be adjusted. The solution may be repeated in an iterative process to find the minimum channel dimensions which can support the new tidal prism. Other factors such as increased coastal erosion may exert a controlling influence on the dimensions of the real channel but it is likely that with the tidal cycle, the actual dimensions will oscillate around this mean. The expected tidal range in the inlet and channel dimensions can then be used to derive building or development limits.

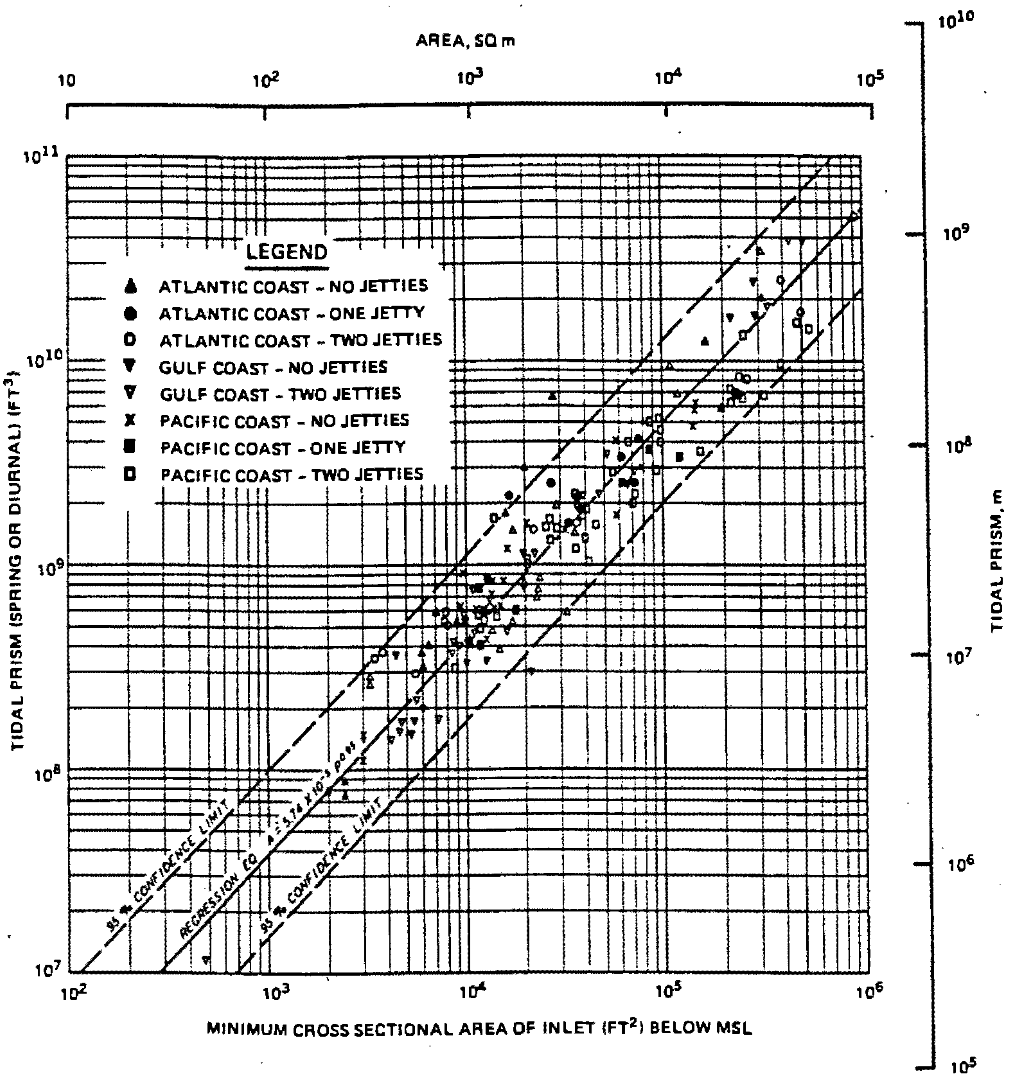


FIGURE 9. Jarrett's empirical relationship between tidal prism and channel cross sectional area for all inlets on the Atlantic, Gulf and Pacific coasts of the USA (after SPM, 1984a).

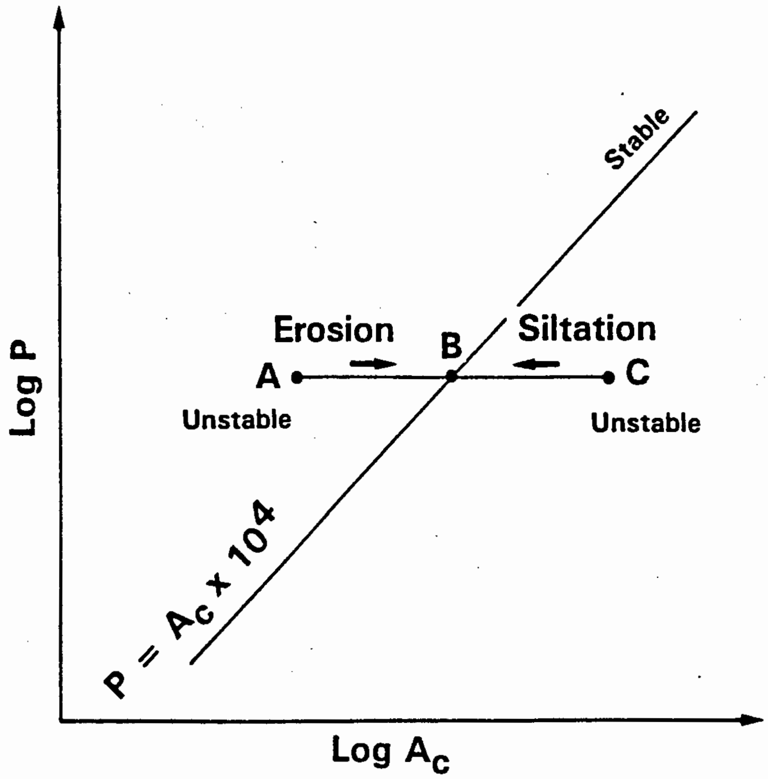


FIGURE 10. Jarrett's empirical relationship between mid-tide cross sectional area of inlet channel and tidal prism. An inlet at position A will erode its channel, increasing A_c and will tend towards the stable dimensions at B. An inlet at C has too large a channel which will silt-up as its dimensions tend towards B. This example is for a short channel length where changes in channel width will not appreciably alter the tidal prism. The slope and shape of AC is a function of the channel length and section which will in turn affect the prism. Long channels will tend to have steeper AC.

King's Solution

Based on observations and recommended coefficient values (K_{en}, K_{exit} and f), a non-dimensional channel coefficient (K_1) and inertia coefficient (K_2) may be calculated;

$$K_1 = \frac{a_s A_b}{2L A_c} \left[K_{en} + K_{exit} + fL \frac{(B+2d)}{4 A_c}\right] \quad (7$$

$$K_2 = \frac{2\pi \sqrt{(LA_b)}}{T \sqrt{(gA_c)}} \quad (8$$

where g is the acceleration due to gravity and T is the tidal period. A_b is the flooded area at MSL, d, B and L are the channel depth, width and length respectively and a_s represents the open water tidal amplitude. The coefficient values recommended for a sandy bottomed inlet by the US Army Corps of Engineers (SPM 1984b) are given in Table 2.

TABLE 2 Recommended coefficient values for a sandy bottomed channel (SPM. 1984b).

$$f = 0.003$$

$$K_{en} = 0.2$$

$$K_{exit} = 1.0$$

K_1 and K_2 are then used in conjunction with design curves (Figs 11 and 12) to obtain a non-dimensional maximum channel velocity ($V^1{}_m$) and ratio (α) of inlet (a_b) to open water tidal amplitude (a_s). These non-dimensional quantities may then be converted to their dimensional counterparts by:

$$a_b = \alpha a_s \qquad (9$$

$$V_m = \frac{2\pi}{T} \frac{A_b a_s V^1{}_m}{A_c} \qquad (10$$

where V_m represents the maximum channel velocity in the inlet channel and T is the tidal period.

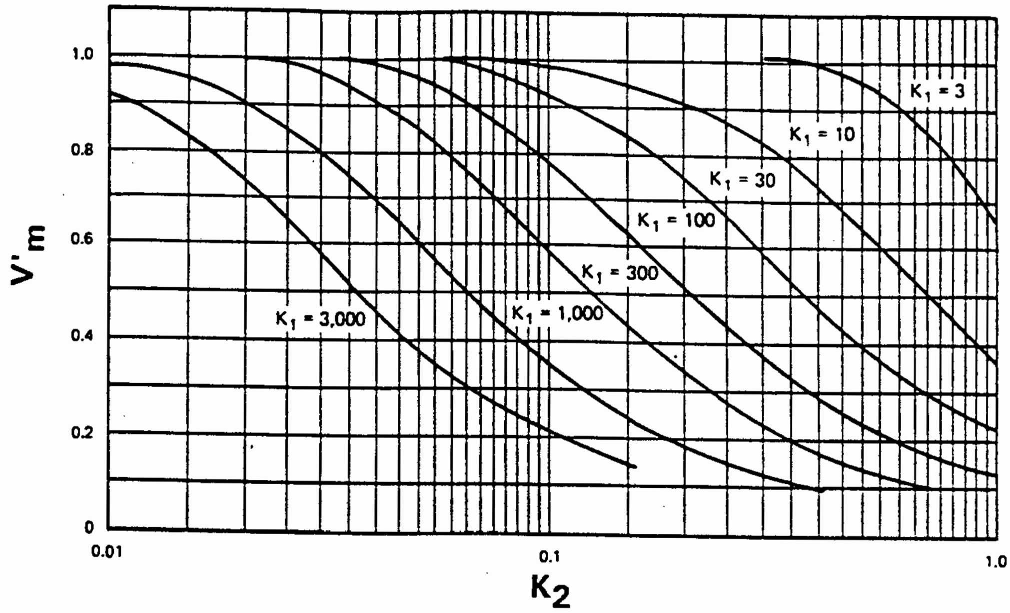


FIGURE 11. Dimensionless maximum velocity versus K_1 and K_2 (after SPM 1984b).

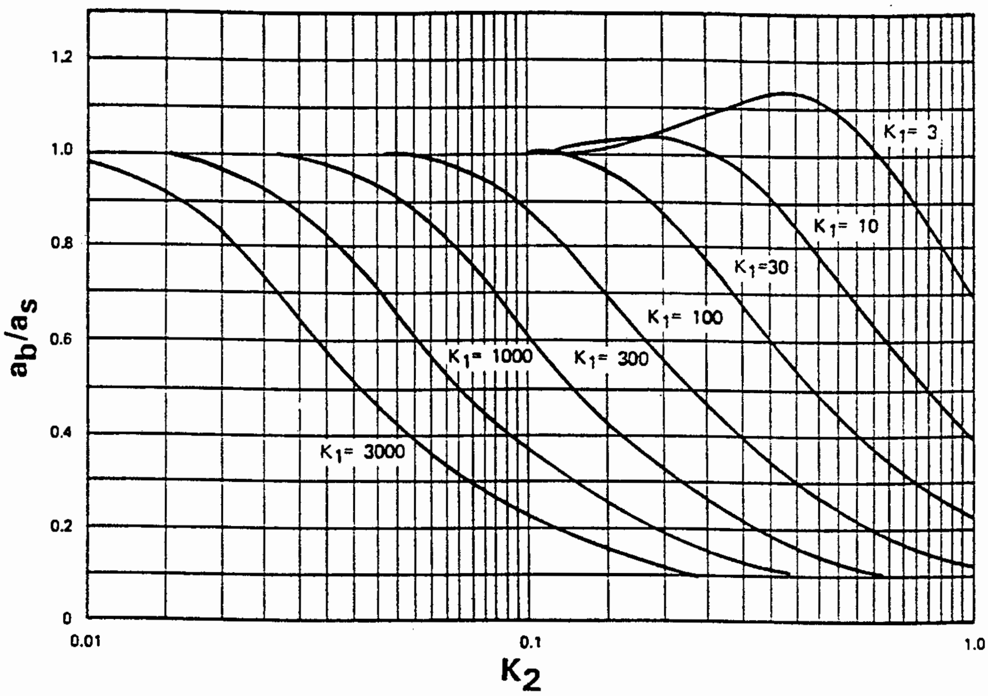


FIGURE 12. Ratio of bay to sea tidal amplitude versus K_1 and K_2 (after SPM 1984b).

The inlet's tidal prism is found directly from α by:

$$P = 2A_b \alpha a_s \qquad (11$$

The calculated prism value is compared with Jarret's empirical stability relationship and if found to be inconsistent, channel dimensions are adjusted and the process repeated.

Note that if the mouth is not fixed it may migrate along the shore and combined with the effects of increased coastal erosion, the channel length may alter. With an increased tidal range, the volume of sediment trapped by the flood delta may be expected to increase. Flood tidal deltas act as sediment sinks and this may add to the increase in coastal erosion on the downdrift side of the inlet and speed up the rate of migration of the mouth.

3.1:3 Salt water intrusion and elevated coastal groundwater tables.

The elevation of the coastal water-table is assumed to increase at the same rate as the rising sea levels if no external forces are acting on the water-table. Like the areas vulnerable to flooding (3.1:2), low lying areas which are known to have high water-tables and have a potential for waterlogging may be interpreted from the most detailed topographic maps available.

Salt water intrusion into coastal aquifers may be modelled using the relationship between surface slope (s), sea level rise (a) and shoreward displacement of the interface (Δx) :

$$\Delta x = a/s \qquad (12$$

This relationship assumes a stable wedge position. However, in most cases the stability of the saline wedge and water-table are (or can be) controlled by extraction of water in nearby wells. Since future extraction rates are unknown, estimates of potential impacts on water-tables and aquifers assume current stable conditions. The relevance of modelling increased salt intrusion in aquifers without a detailed freshwater extraction plan is therefore questionable.

Saline intrusion into estuaries is a primarily a function of river flow, bed slope and form. The modelling of the extent of increased intrusion into all of South Africa's rivers is a complex problem worthy of a study in its own right. Consequently detailed modelling is not considered here save to acknowledge that an increase in intrusion will occur in most estuaries.

3.1:4 Storm damage.

With elevated water levels, smaller and therefore more frequently occurring storm events will overtop existing sea defences. In other words, with rising sea levels the effective protection afforded by existing sea defences will be reduced.

The elevation of coastal water levels during storms may be modelled by adding storm surge, from a storm of known return frequency, to the set up from design waves for that shore. Addition of these levels to the new MHWS after sea level rise provides an estimate of potential new coastal water levels during storm conditions. Where possible, the Joint Probabilities Method (Pugh & Vassie 1980, Searson *in prep.*) is used to provide storm water level probability curves to which set-up from the appropriate design period waves and sea level rise may be added. Figure 13 shows an example of a return period curve for Simon's Town to which 10 cm, 20 cm and 50 cm of sea level rise have been added. Unfortunately these storm curves are not yet available for the whole country (Searson *in prep.*) but it is felt that the surge + set-up + new MHWS method is of sufficient accuracy for this study. Once the new storm levels are established, those low lying areas adjacent to the coast which may be vulnerable to storm flooding are interpreted from the most detailed topographic maps available. Storm induced erosion is only modelled for one location in this thesis but due cognisance of this short term storm erosion must be given in all cases.

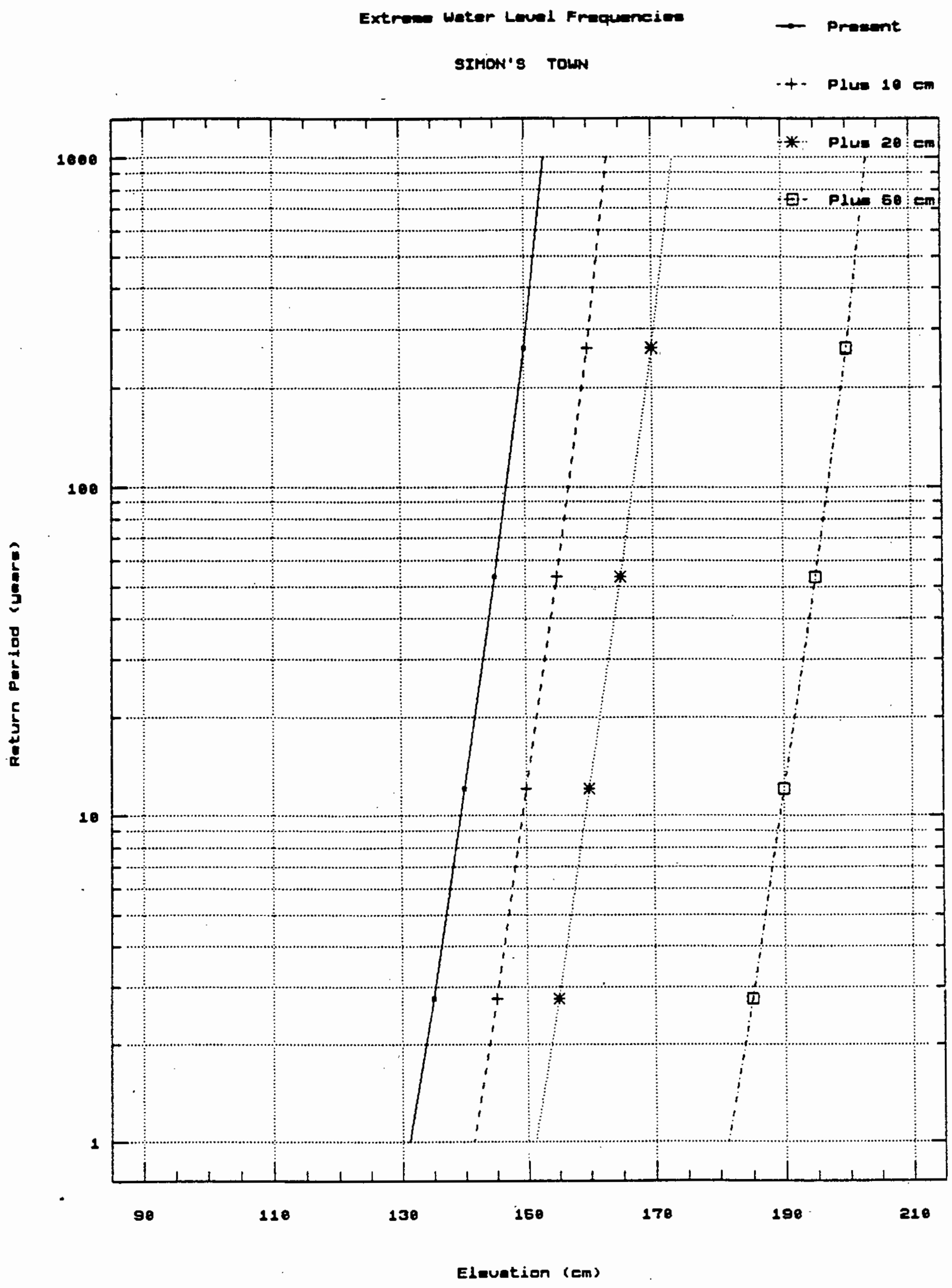


FIGURE 13. Extreme water level frequencies for Simon's Town, sea level increments of 10 cm, 20 cm and 50 cm are shown (after Searson *in prep.*).

3.2 The Approach.

After a preliminary assessment to determine if a location is potentially vulnerable to sea level rise, the steps taken to evaluate the possible impacts and estimate the morphological changes may be summarized:

1. Increased coastal erosion; Modelled by application of the Bruun Rule (1962) in its simplest form (equation 3). Where significant longshore variability in sediment transport rates is apparent, extensions are used to account for this (equations 5 and 6). This provides a best estimate of the future shoreline location on a soft erodible coast but due cognisance must be given to the presence of rocky outcrops which will reduce the amount of erosion.
2. Increased flooding and inundation; Important in sheltered environments and modelled by application of King's non-dimensional solution to determine the minimum channel dimensions which can support the newly flooded area (equations 7-11). On the open coast the sea level rise is added to the MHWS or HAT.
3. Increased saline intrusion; Where detailed knowledge of the saline wedge in a coastal aquifer is available, the increased intrusion is modelled by the shoreline gradient : sea level rise relationship (equation 12). In the absence of detailed knowledge, the magnitude of the sea level rise is added to the elevation of the coastal water-table. Both cases assume the water-table is stable and that there are no changes in extraction rates.
4. Reduced protection from extreme event; Coastal water levels are modelled by summing the "storm surge" and wave set-up for a design storm and waves. Sea level rise is added to this level to determine future storm flood levels. "Storm surge" return frequencies are calculated by application of the Joint Probability Method (Pugh and Vassie 1980, Searson *in prep.*) or estimated from tide gauge and atmospheric records. Storm erosion is not modelled for three case studies but a "safety margin" may be estimated from historical evidence and personal communications.

Having discussed the methods which may be combined to assess the potential impacts of sea level rise and geomorphological changes on the South African coastal environment the next step is to determine how to apply them to the whole coast. Ideally, for the most complete assessment, these methods should be applied to all locations, on an individual basis, around the whole coastline. However, this approach would be clearly inefficient in terms of effort required at this level of investigation and would certainly be a laborious task which could never be completed in the time allotted for this study.

The preferred approach for this study therefore was to select a number of sites which may be considered typical or representative of environments found around the whole coastline. Having selected locations with these environments types, detailed case studies were carried on them for a range of sea level rise scenarios assuming a continuation of the present climatic conditions. In each environment type the most critical processes and impacts were identified and the possible management options considered. Sites were chosen to represent:

1. Partially developed shorelines with river mouths, estuaries and backing wetlands and lagoons.

2. Developed coastlines with some room for manoeuvring of coastal buffer zones with potentially a wide range of possible impacts.

3. Heavily developed coastlines, backed by hard structures with no buffer zones, no room for manoeuvring and a high risk of storm damage and flooding via an estuary during storms.

4. Lightly developed and moderately sheltered coastlines in extremely dynamic sedimentary environments with a dependance on coastal aquifers. In many respects this location is analogous to a sheltered tidal inlet.

The locations of Woodbridge Island (Milnerton), False Bay, Durban and Walvis Bay were chosen to represent these four environments respectively (Table 3). Having gained an understanding of the way in which the "type-locations" were expected to behave under rising sea levels and the critical processes involved, the question of regional vulnerability arises.

The application of a Coastal Vulnerability Index (CVI) (Gornitz & Kanciruk 1989) designed for global application was reviewed and considered but found to have too coarse a resolution for successful application in this country. In addition the CVI does not consider the processes involved in the impacts nor does it convey any sense of vulnerability in societal terms. A new CVI was developed which incorporated these factors (Hughes & Brundrit 1991a) and regional vulnerability was assessed drawing on the experience gained from the case studies to estimate likely impacts. The results of this risk analysis produced ranked lists of those most vulnerable locations overall, the most vulnerable infrastructure in those locations and the most serious hazards to that infrastructure. From the regional assessments in "type regions" a picture of the likely vulnerability of the whole coastline was built up and possible management strategies for South Africa could then be considered.

Chapter 4

DETAILED CASE STUDIES OF THE IMPACTS OF SEA LEVEL RISE IN REPRESENTATIVE ENVIRONMENTS

In this chapter, a number of detailed case studies of the impacts of sea level rise are presented in a condensed form in order to demonstrate the vulnerability of the "type locations" described in chapter 3 to rising sea levels. In doing so the key processes for deleterious effects are identified. In the first three case studies the impacts of sea level rise are considered in reverse chronological order,- i.e. a maximum or worst possible case scenario is examined to identify the most vulnerable areas and demonstrate which are the critical processes. Once identified the magnitude of sea level rise is scaled down to more realistic values in order to determine a pseudo-time scale on which to measure the occurrence of the "first serious impact" in that vulnerable area. The impacts are then discussed and possible management options considered. Note that although the case study locations where chosen to be representative of "type environments," all are in urban or built up areas. The case studies are carried out to highlight the impacts of sea level rise (on society) and not just to determine the expected geomorphological changes expected with rising sea levels. Hence the use of urbanised sites. Greater detail of the case studies may be found in Hughes et al. (1991b), Hughes and Brundrit (1991c), Hughes and Brundrit (1990) and Hughes et al. (1991c). Table 3 summarises some of the environmental parameters of the sites.

LOCATION	EXPOSURE DIRECTION	WAVES (m) (AFTER CSIR 1984)	DOMINANT WAVE DIRECTION	TIDAL RANGE (m)	DOMINANT WIND DIRECTION	SHOREFACE DESCRIPTION
	General Local	H_s 0.01% exceedence H_s 0.1% exceedence H_s 1.0% exceedence		Spring. Highest Astronomical		
Woodbridge Island	W	8.3 6.5 4.8	SW Sheltered from the South	1.42 2.01 ± 0.3 m shelf wave	Biomodal: NW Winter SE Summer	Sandy dune barrier slightly sheltered from the north, dunes to ± 10 m high, backed by ephemeral estuary and wetland. Development close to waterline with minimal buffer zone. Slight northerly net longshore sediment transport.
False Bay	Two sides of a bay S - Sheltered W - More exposed	9.3 7.5 5.6	SW	1.48 2.07 ± 0.3 m shelf wave	Biomodal: NW - Winter SE - Summer	Western seaboard: Rocky with sheltered sandy pocket beaches. Dunes < 3 m if present and development well set back from shore. Northern seaboard: Sandy coast with occasional rocky outcrops. Major development close to waterline in places, room for buffer zone elsewhere. Shore contains a low lying marina/inlet.
Durban	NE/SW N/S	5.5 4.5 3.5	SSW & NE	1.72 2.32	Biomodal: SW - Winter NE - Summer	Nourished sandy beach backed by intense city development with retaining and sea walls. Offshore profile altered, causing wave focussing. Considerable northwards longshore sediment transport. No room for buffer zone. River mouth with city built on old river course.
Walvis Bay	SW ± W	3.8 3.1 2.5	S	1.42 1.97 < ± 0.1 shelf wave	SSE	Very dynamic desert sedimentary environment with town sheltered from waves by large sandy spit. Very low lying and flat coastline. Development impossible in most dynamic shoreline areas but possible in sheltered sections where it is very close to the waterline.

TABLE 3. Environmental parameters for case study locations.

4.1 The Impacts of Sea Level Rise on the Woodbridge Island/Diep River System.

The study area is the coast and low lying area immediately adjacent to the mouth of the Diep River approximately 5 km north of Cape Town (Fig. 14). The main features are a tidal inlet (Milnerton Lagoon) and wetland system (Rietvlei) which open onto an essentially unconsolidated coastline. The eastern periphery of the system is an increasingly developed residential extension of the municipality of Milnerton. The mouth of the river is generally closed in the summer by the development of a low berm which is overtopped by high spring tides. A portion of the spit on the seaward side of the river near its mouth, known as Woodbridge Island, is an intensely developed residential area with houses within 2 m elevation of the current MHWS (CSIR 1983). To the north of Woodbridge Island the primary dunes are moderately well vegetated with some blow-out features and are backed by a golf course at a lower elevation. The toe of these dunes and the hummocky dunes fronting Woodbridge Island are scarped - indicating a certain amount of wave erosion probably during winter storms. Occasionally the sea washes over onto the golf course through a low gap approximately 100 m north of the lighthouse. Under normal conditions only swells from a section between 260° and 330° reach the area with swells from the northwest (300-315°) being influenced by Robben Island. Under certain conditions, swells from a wider distribution can reach the area by refraction and diffraction around the Peninsula although the overall effect of the Peninsula and Robben Island is to reduce deep water wave heights of most swells except for those from the west and northwest.

The nearshore sediment is fine beach sand with occasional shelly patches and gravel lags and is in the region of 10 m - 20 m thick (Woodborne 1983, CSIR 1972) increasing to more than 25 m within 1 km landward of the shore. Surface and deep water currents in Table Bay are dominated by the local wind direction and the only significant sediment transporting currents occur in the surf and nearshore zone as a result of combined wind and wave action (CSIR 1972). Winds tend to be north-westerly in winter and south-easterly in summer. Sediment distributions off the Diep River mouth suggest a bimodal transport but the net transport direction at Woodbridge Island is northwards to which CSIR (1972) has put a value of approximately 100,000 m^3/year. This value may be an over-estimate but the south side of the river mouth is sediment starved and is actively being eroded - witness large dune scarps, the use of dolos for protection to the south and the recent discovery and uncovering of a number of 17th century wrecks just offshore.

Historically the Diep River has shown a high degree of mobility with an early map from 1786 showing its mouth some 3 km to the south of its present position. This shoreline has been a state of accretion between at least 1780 and 1900 (CSIR 1988a) but since 1900 the situation has reversed and approximately 80 m of erosion on Woodbridge Island has taken place (CSIR 1983). This reversal has been attributed to wave reflections from large scale extensions to Cape Town Harbour and a further 10 m of long term erosion is expected to take place at Woodbridge Island (CSIR 1983).

In short this section of coastline is soft and erodible, has historically shown a high degree of mobility, is currently being eroded and is exposed to westerly and north-westerly storms. The predominant southwesterly swell is generally much reduced by the presence of the Peninsula.

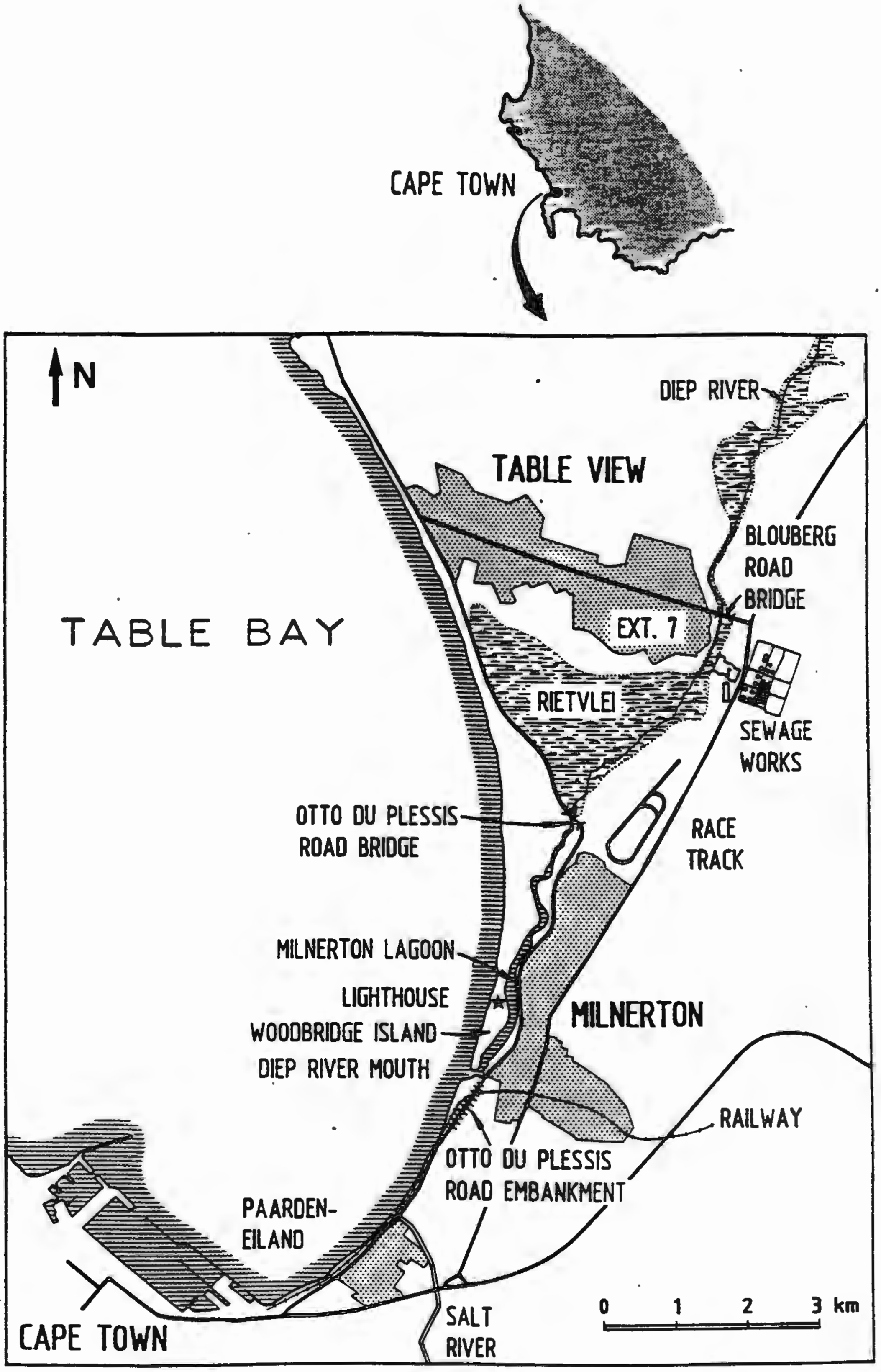


FIGURE 14. Location of study area, approximately 5 km north of Cape Town (after Hughes et al. 1991b).

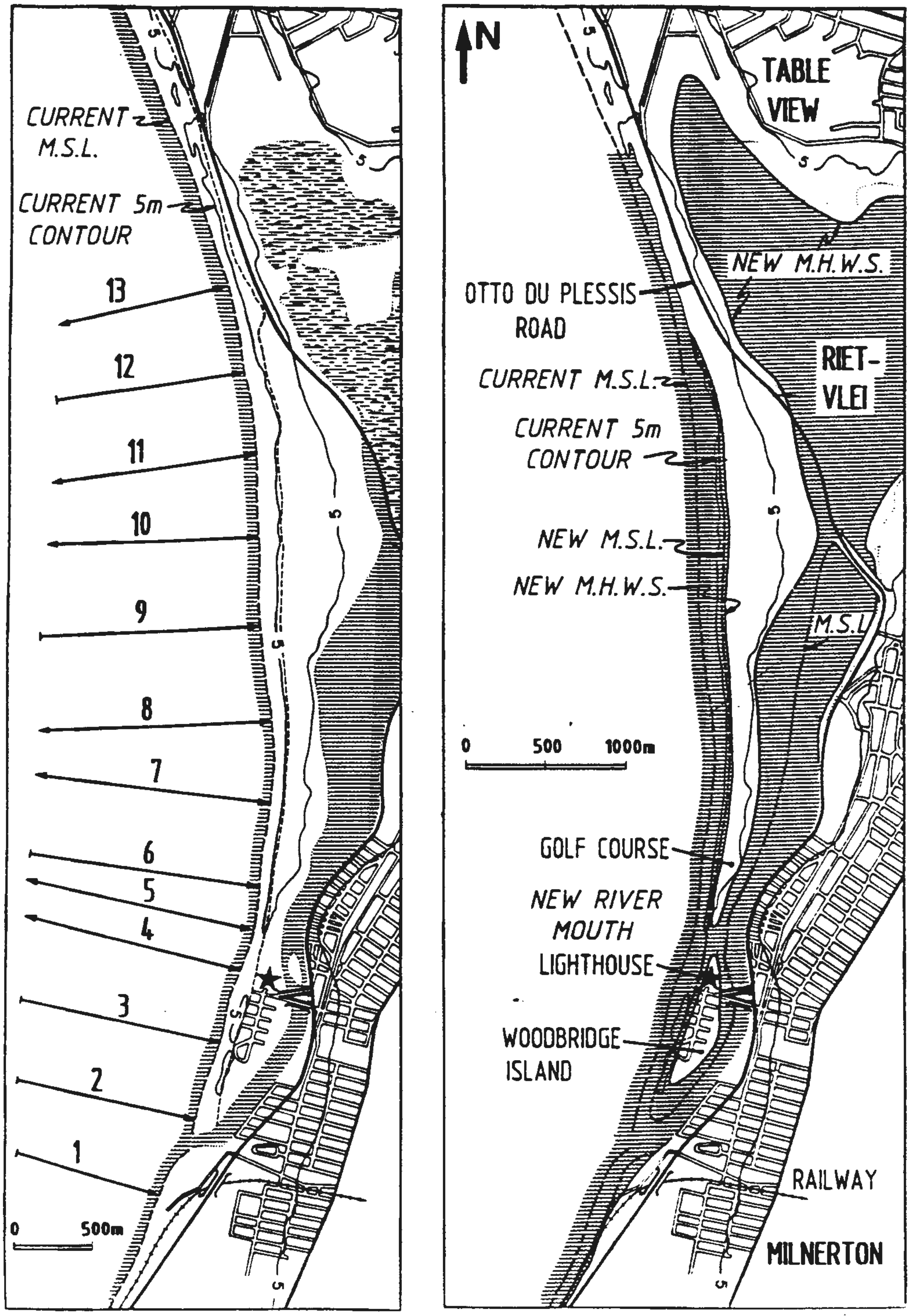


FIGURE 15. Location of the profiles to which the Bruun Rule was applied and the position of the new shoreline after a 1 m rise in sea level (after Hughes et al. 1991b).

4.1:1 Impact of Increased Coastal Erosion

Application of the Bruun Rule (1962) assumes a total profile shift and that the relative summer and winter profiles will not change significantly with sea level rise. An "average" profile was assumed and the nearshore and offshore bathymetry was taken from the most recent South African Navy hydrographic chart (SAN 1014) with topography taken from maps obtained from Milnerton Municipality.

Thirteen sections were drawn normal to the coastline at approximately 250 m to 500 m intervals. Longshore gradients in sediment transport rates are uncertain and the Bruun Rule (Bruun 1962) was applied in its simplest form for a rise in sea level of 1 m (C3.1:1, equation 3).

Table 4 shows the maximum calculated erosion for the thirteen profiles. Fig. 15 shows the location of these sections and positions of the new shoreline relative to its present position after a 1 m rise. Note an additional 10 m of long term erosion was added to allow for the remaining changes due from the harbour extensions.

Profile 5 is highlighted in Fig. 16 as it shows that the transgression will break through to the Milnerton Lagoon at the new MHWS (1.86 m elevation) after a rise in sea level of 1 m. In practise, when considering the effects of storm surge and wave attack, the breakthrough is likely to occur prior to the full 1 m rise. Once open the breakthrough will probably remain open, effectively shortening the channel length from the open sea to Rietvlei by some 1500 m. It is also likely that fluvial action and human interference from behind will prevent the migration of the dune barrier landward.

TABLE 4 Coastal recession in metres at Woodbridge Island as indicated by application of the Bruun Rule (1962) (after Hughes et al. 1991b).

	EROSION (m)	
PROFILE	1.0 m Rise	0.5 m Rise
1	135	68
2	115	58
3	80	40
4	75	38
5	80	40
6	70	35
7	80	40
8	80	40
9	65	33
10	60	30
11	55	28
12	65	33
13	60	30

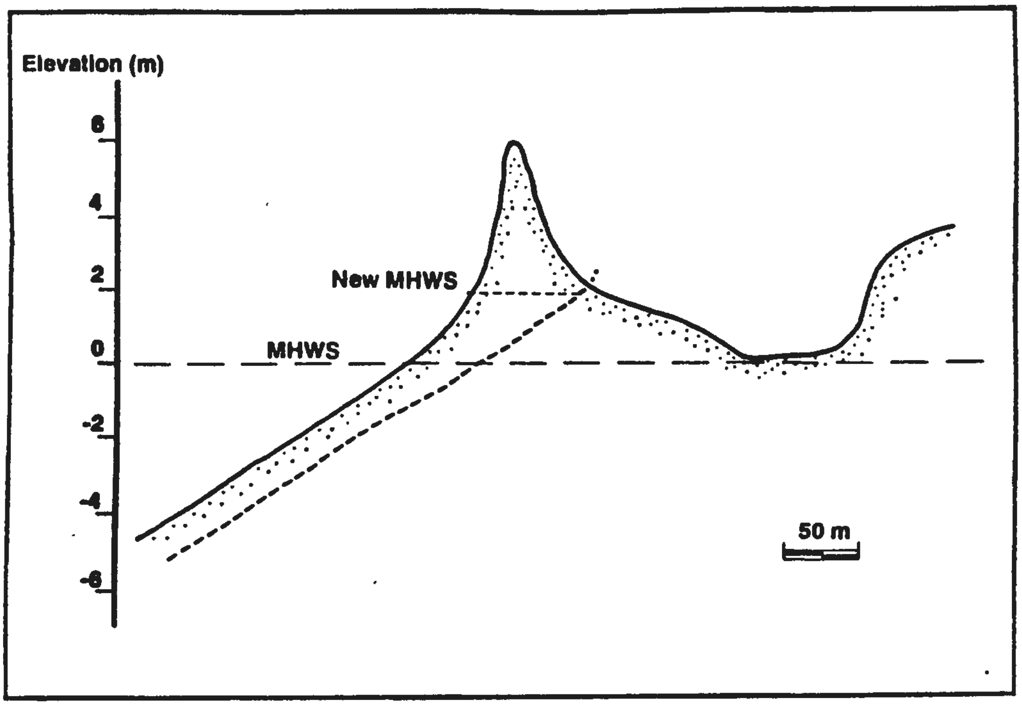


FIGURE 16. Detail of Profile 5 showing the break-through point to Milnerton Lagoon after a 1 m rise in sea level (after Hughes et al. 1991b).

4.1:2 Impact of Flooding and Inundation

With a rise in sea level, low lying areas of land open to the sea may be anticipated to flood with sea water. Rietvlei will effectively become a large shallow body of sea water connected to the sea via a long narrow channel - the Milnerton Lagoon. In Table Bay, after a rise of 1 m in sea level, MSL and MHWS will change from 0.15 m and 0.86 m elevation to 1.15 m and 1.86 m respectively. Inside the wetland system, MSL will also be at 1.15 m elevation but frictional losses in the channel will reduce the tidal range. This range may be calculated using Jarrett's and King's methods described in C.3.1:2. The following dimensions are used;-

The bottom of the vlei is assumed to be a smooth surface with gradient taken from the relative separation of the 0 and 2 m contours, the area flooded at MSL (A_b) (1.15 m elevation) may be calculated to be of the order of 1.72×10^6 m^2. The channel is assumed to be a uniform depth (d) 1 m below MSL, 150 m wide (B) and 4,000 m long (L).

Using these values the inlet's tidal prism will be 1.61 x 10^6 m^3 and the tidal amplitude in the inlet will be 0.47 m.

The calculated tidal prism using King's solution (SPM 1984b) is in good agreement with the Jarrett's empirical stability criterion (shown in C.3.1:2) and the expected tidal channel should therefore not enlarge itself beyond its present dimensions under normal flow conditions. MHWS inside the vlei should be around 1.62 m (1.15 m + 0.47 m) - i.e. the tidal range in the vlei will be approximately 66% of the open water value.

However, as previously discussed, the effects of increased coastal erosion and breakthrough of the coastal dunefield will shorten the channel length to 2500 m. Using King's solution (SPM 1984b) in an iterative process and assuming a channel depth of 1 m, a channel width of 185 m would be required to satisfy Jarrett's stability relationship (C3.1:2, SPM 1984a). This shorter, wider channel with its lower resistance to flow will allow for an increased tidal range within the vlei. This range will be of the order of 1.3 m (0.64 m x 2) or 90% of the open water value, putting the MHWS level in the inlet at 1.79 m elevation during calm conditions. The tidal prism will be approximately 2.1 x 10^6 m^3. Fig. 17 shows the extent of inundation at MHWS in the vlei.

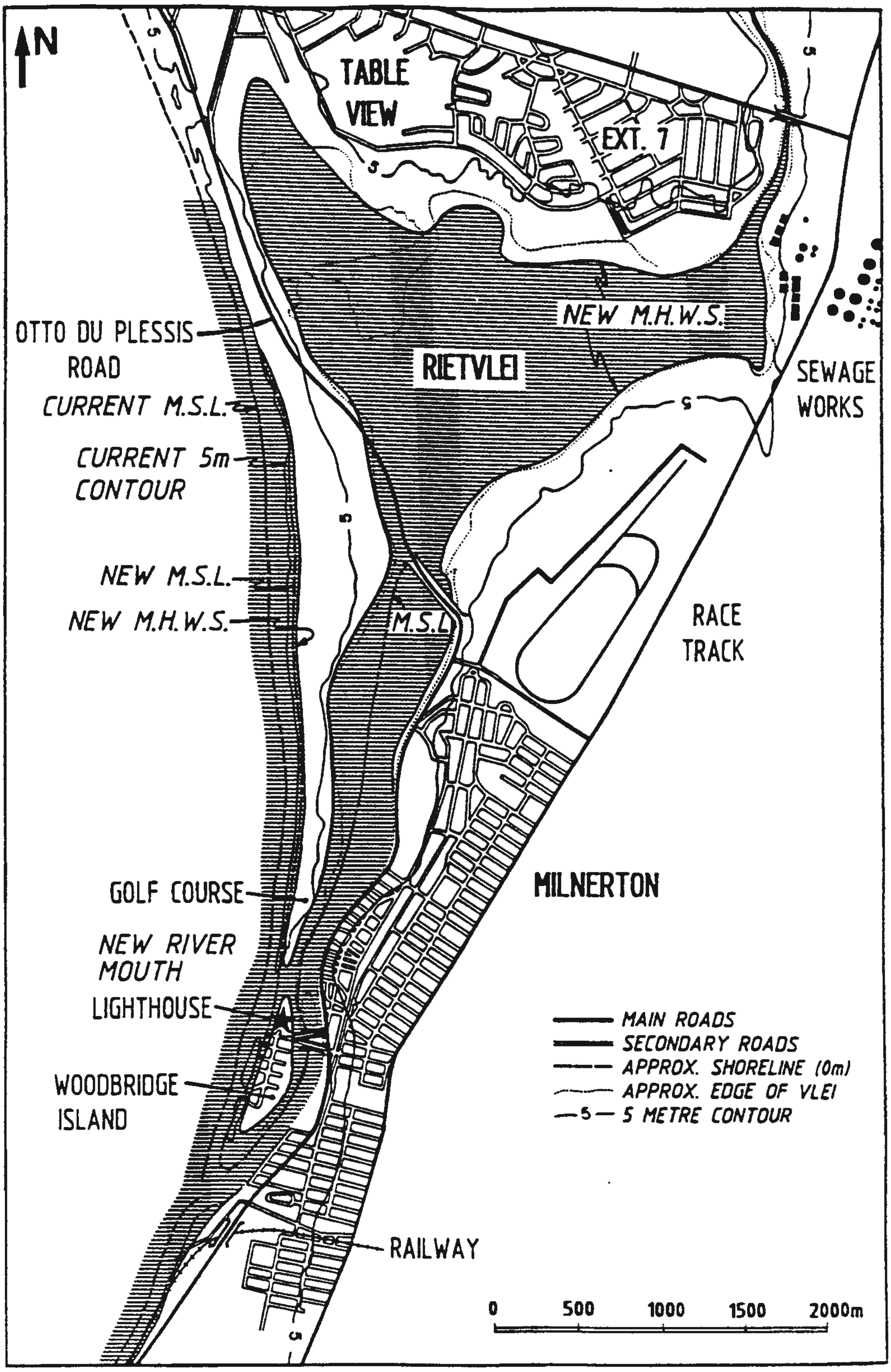


FIGURE 17. Position of the new shoreline and new MHWS in Rietvlei after a 1 m rise in sea level (after Hughes et al. 1991b).

4.1:3 Increased Salt Water Intrusion and Elevation of Coastal Groundwater Tables

The bulk of freshwater used in Milnerton is not obtained locally from the coastal aquifer. Water in the aquifer is brackish and is only used in certain instances for garden irrigation (R. Stanley, Milnerton Municipality *Pers. Com.* 1989). Increased salt pollution of the aquifer will not therefore have any major effect on freshwater supplies and consequently detailed modelling of the position of the saline wedge has not been carried out.

However, as a result of raised groundwater tables, parts of the study area may experience problems such as waterlogging and increased seepage into basements. The present and likely problematical areas are known to the Town Engineer and are generally quite local in extent (Stanley, *Pers. Com.* 1989) and unlikely to cause any major problems. The presence of a high watertable tends to discourage much development in these areas but further detailed investigation of the groundwater is recommended in order to facilitate a management plan.

4.1:4 Reduced Protection from Extreme Events

Due to property development on Woodbridge Island a considerable amount of work has already been done on predictive models for storm erosion. These models (CSIR 1986, Hughes et al. 1991a) suggest that the maximum coastal erosion for a 1 in 50 year storm is 25 m. This calculation assumes a linear dune barrier with no breaks. Gaps do occur, allowing washover and therefore this value is likely to be an underestimate in places. The erosion caused on Woodbridge Island by the infamous May 1984 storm - an approximate 1 in 40 to 50 year storm, was 34 m - i.e. in good agreement with the actual value.

This amount of storm erosion occurring after a 1 m rise would probably be sufficient to erode half of Woodbridge Island, widen the breakthrough point on the river bend to about 500 m thereby exposing the Milnerton coastline to direct wave action and erode the dunes to the north of the Island by 20-25 m. Fig. 18 shows the effects of 25 m of erosion applied to the new MHWS of the +1 m sea level scenario.

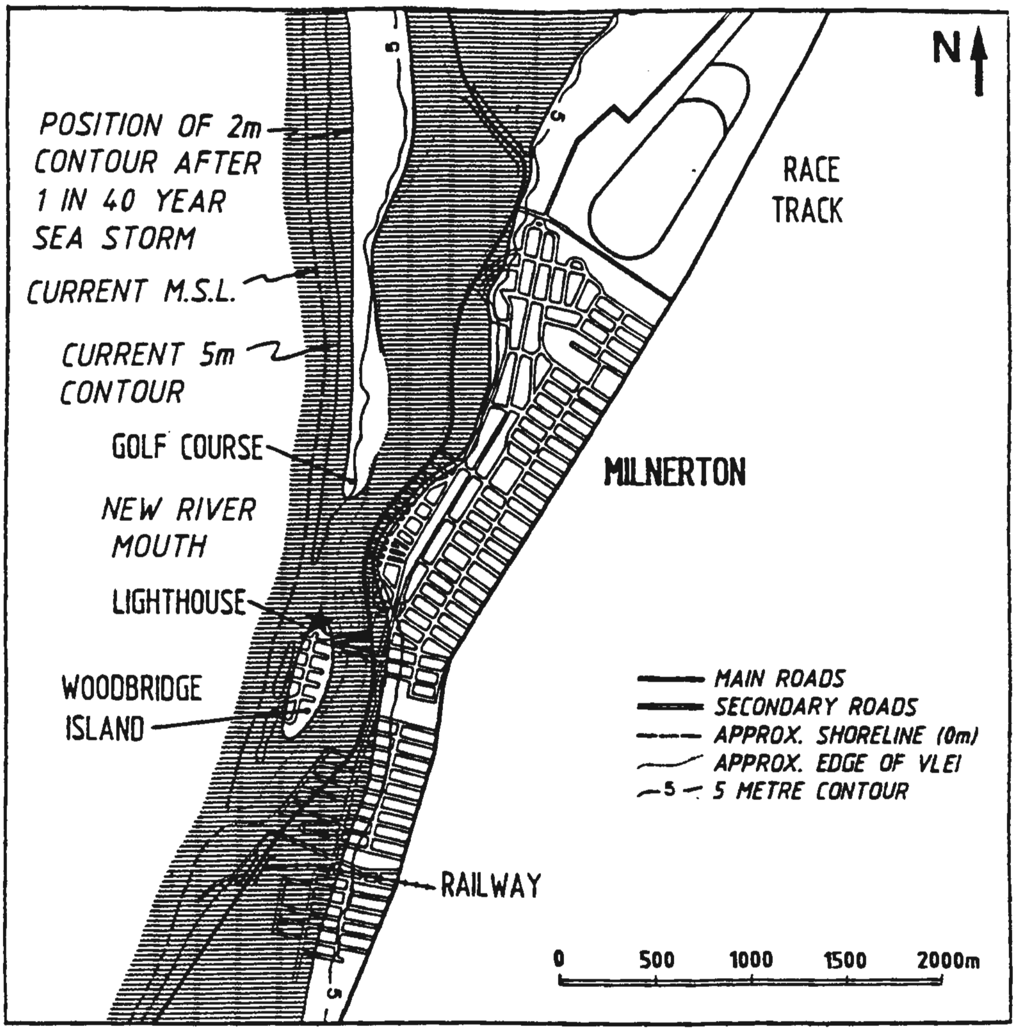


FIGURE 18. Shoreline position after an additional 25 m of coastal storm erosion and the storm flood level from a 1 in 40 to 50 year storm (after Hughes et al. 1991b).

Storm surge and wave set-up during the 15-16 May 1984 was estimated to be 1.2 m (Jury et al. 1986). If this type of storm were to re-occur after a 1 m rise in sea level on a high spring tide, the water level could be up to 3 m elevation (1.0 m + 0.86 m + 1.2 m) relative to land levelling datum. This level would completely swamp Woodbridge Island and flood all those parts of Milnerton adjacent to the shoreline below 3 m elevation (Fig. 18).

Surge of this magnitude would certainly penetrate into the lagoon and the flooded vlei via the shortened channel thereby extending the area of potential flooding and swamping the Milnerton shoreline (Fig. 18). A combination of such a sea storm and heavy rainfall or river flooding would further exacerbate the problem.

4.1:5 Discussion

From the above presentation of the impacts of 1 m of sea level rise on this coastline it is clear that Woodbridge Island and Milnerton would be seriously affected by increased coastal erosion, inundation and storm damage.

In the event of no protection work being carried out the sea will in all likelihood break through to the river on the bend north of the lighthouse, opening a second mouth 185 m wide, allowing greater flooding of the vlei and direct wave action to impinge on the Milnerton coast (Fig. 17). The tidal range within the inlet will be of the order of 90% of the open water value. The second major impact is the vulnerability of the area to storm damage; a large storm of a 1 in 40 to 50 year order magnitude, will be sufficient to seriously erode Woodbridge Island and cause significant storm damage to the entire Island and the first few streets in Milnerton. Parts surrounding the inlet may be seriously affected and although the timing of such a storm is impossible to predict, the probability of its occurrence must not be ignored.

Now that the most serious impacts have been identified in a worst case scenario the question is, what magnitude of sea level is required before any real danger exists?

By tackling the problem of increased coastal erosion using 50 cm of sea level rise it can be seen that a 50 cm rise plus 10 m of long term erosion, applied to the problematical Profile 5, will leave a gap between MHWS and the crest of the dune of 30 m in plan and 1.5 m in elevation. This 50 cm is probably therefore the maximum amount of rise possible before a storm would break through that narrow margin. The first breaching may not necessarily complete the opening of the second channel but would certainly lay the west side of Milnerton open to direct wave action and facilitate subsequent breachings. Applying King's solution in an iterative process for the long <u>un</u>breached channel with 50 cm of sea level rise suggests that the current channel dimensions are sufficient to cope with future flows and the tidal amplitude inside the bay will be 0.5 m or 70% of the open water value. At MHWS approximately 2/3 of the vlei will be flooded.

Table 4 shows the estimated erosion of profiles 1 to 13 for 50 cm rise in sea level. Erosion of this magnitude combined with the 10 m of long term erosion in the Woodbridge Island area would be just survivable for the houses on the Island in the absence of major storms. The occurrence of any major storms (e.g. 25 m type erosions) would seriously affect these houses.

Fig. 19 shows the storm surge re-occurrence curves for Simon's Town which for all practical purposes may be taken as identical to those of Granger Bay near the Cape Town Harbour (Fig. 14) (Searson *in prep.)*. The May 1984 storm recorded a level (in the absence of 0.95 m set up) of 1.49 m elevation. It shows clearly that a rise in sea level of only 20 cm will be sufficient to change the water level achieved by the occurrence of a 1 in 300 year event at present to that of an annual occurrence. Note that these curves do not include any wave set up component and therefore storms with the equivalent flood damage potential to the May 1984 storm could, in theory, happen at less than an annual occurrence. These surges are generally of sufficient duration to penetrate the inlet thereby exacerbating flood problems.

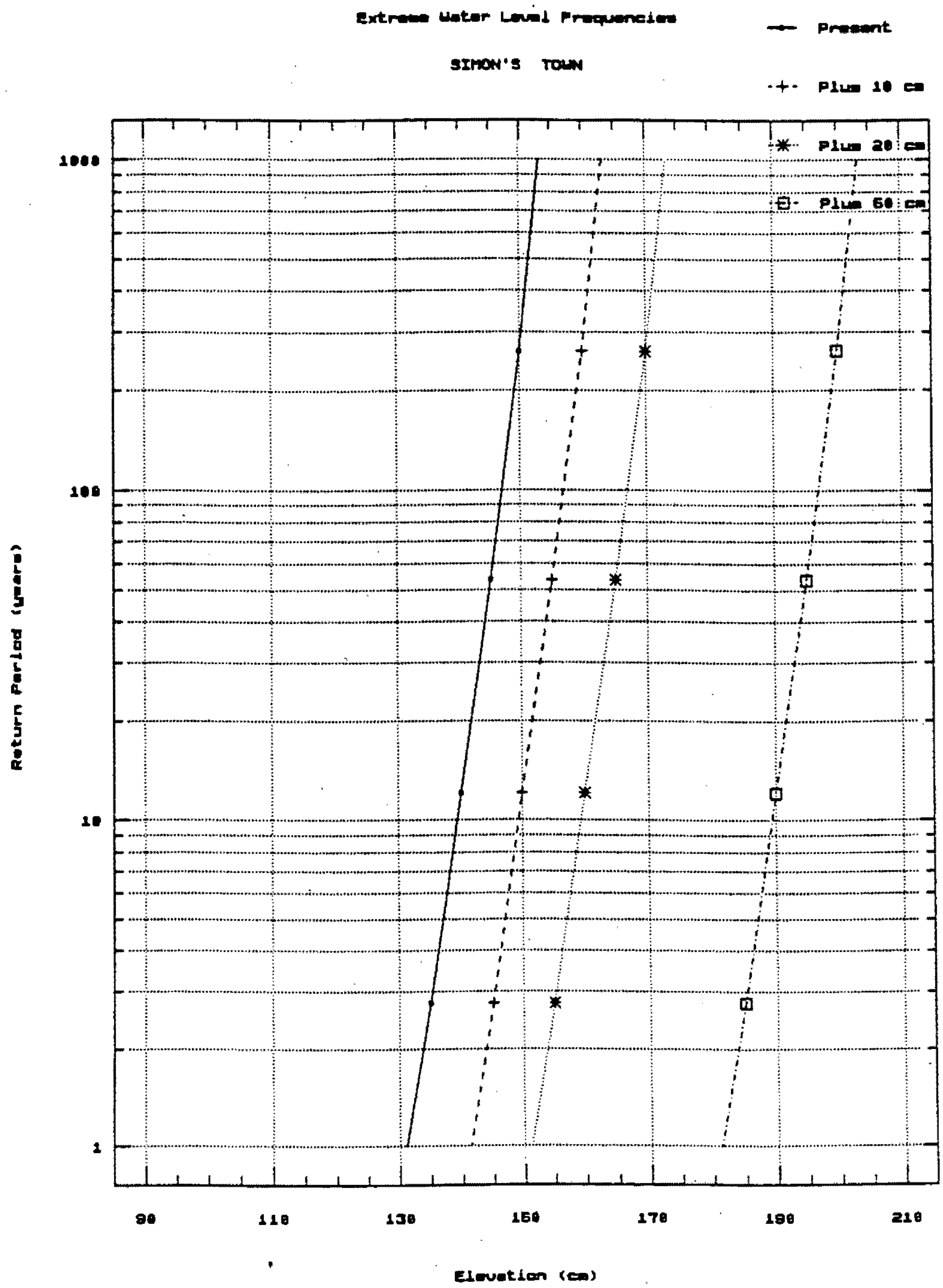


FIGURE 19. Extreme water level frequencies for Simon's Town, sea level increments of 10 cm, 20 cm and 50 cm are shown (after Searson *in prep.*).

4.1:6 Summary

The Woodbridge Island/Rietvlei system is a soft, erodible, partially developed shoreline with a lagoon and backing wetland. There is pressure to develop the coastline and wetland margins further and in some areas this development is already being marketed.

The most serious problems facing this area are:

a) The potential for storm flood damage to the developed spit, town margin and developing margins of the vlei after only a small rise in near future.

b) The potential increased erosion causing breakthrough to the river causing shortening of the channel, a larger internal tidal range and associated increase in potential storm damage in the mid future.

In the absence of protective measures being carried out the latter problem would appear to be the more certain with more permanent impacts although the problem of frequent storm damage must not be dismissed. It is necessary to consider the Management options available. Protection in some form would appear to be necessary along the whole coastline with additional armouring of the dune in the area of Profile 5. In terms of aesthetics and minimal disturbance to the shore face, a beach and dune nourishment programme - possibly with some integral armouring for extreme events - would seem the most desirable. The south shore of the mouth is, to a certain extent, armoured already with rubble and retaining walls, backed by a carpark area and disused road before the main road. Increasing this armourment for protection from erosion and extreme events would also be a consideration. However, in the long term, maintenance of the beach and dune by nourishment may eventually become prohibitively expensive unless complemented by hard engineering and some loss or damage to property may be unavoidable. Detailed surveys are required before any costing of such maintenance can be made. Forced purchasing or property transactions on a leasehold basis may become necessary for some low lying and coastal areas, especially on the spit, in order to preserve the natural beauty of the area.

In terms of storm surge entering the wetland and flooding the developing margins one possible method of ameliorating the problem would be to raise the background water level in the vlei above storm levels now by means of a weir near the mouth. This would flood all potentially vulnerable land now and prevent excessive surge entering the system. Unfortunately this programme is dependent on fresh water input which may not always be adequate in the summer and the flooding may not necessarily make "good ecological sense". In addition it may exacerbate existing river flood problems and it prevents the use of valuable waterfront land.

The potential hazards have been recognized but further studies are required before determination of a final management plan. These studies must include detailed groundwater investigations to identify those areas vulnerable to waterlogging and any possible dewatering schedules. There must also be a balanced approach to the hard versus soft protection predicament. However improvements in the accuracy of sea level rise predictions are probably a prerequisite to management action.

4.2 The Impacts of Sea Level Rise on the False Bay Coastline, Cape Town

The False Bay coastline (Fig. 20) consists of a combination of hard (resistant) and soft (erodible) types of coastlines. The western and eastern seaboards are mostly "hard" and rocky, except for a few sandy bays and pocket beaches such as Glencairn and Fish Hoek. Their location is a generally function of the structural control of the regional geology and usually reflect faults or shear zones.

The northern shoreline is generally softer and is characterized by long sweeping beaches, backed by dunefields stretching between Muizenberg and Gordon's Bay. The dunefields are interrupted by a cliffed section of semi-calcretized aeolianites at Swartklip and there are a few rocky outcrops at the low water mark between Strand and Gordon's Bay.

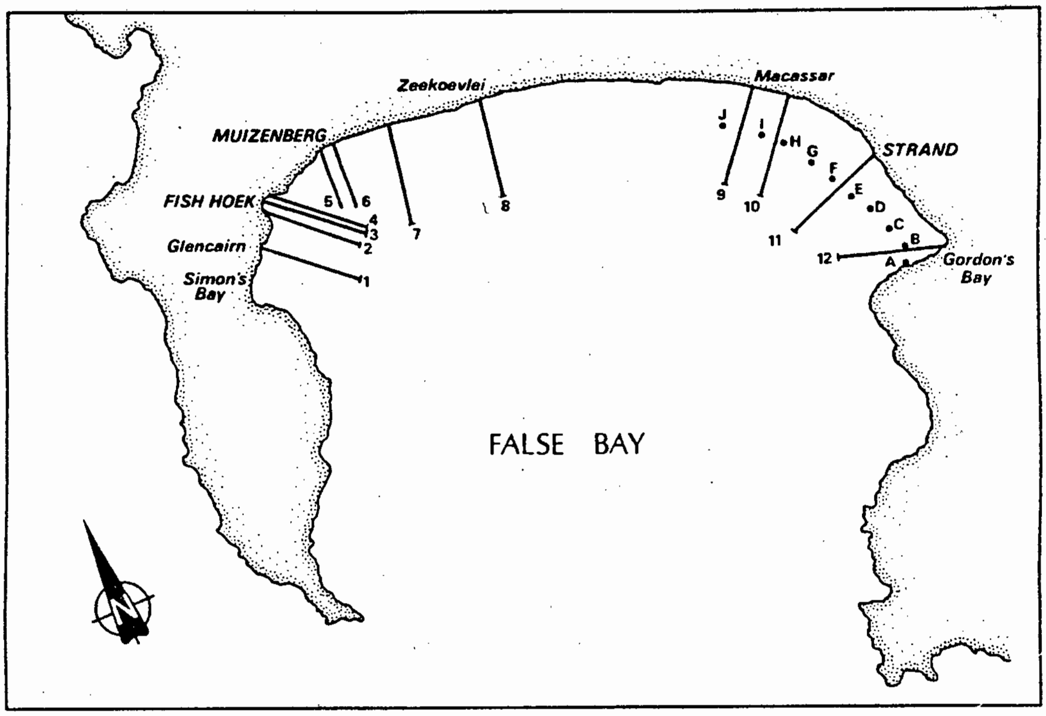


FIGURE 20. False Bay location map showing profiles to which the Bruun Rule was applied and the wave measurement stations referred to in Table 5 (after Hughes and Brundrit 1991c).

Sediments within the beach and nearshore areas of the bay are generally fine to medium grained sands with some coarse sandy patches. The bay is exposed to all swells from a southerly direction and due to wave refraction, orthogonals generally strike the sandy beaches normally. Longshore sediment transport is generally in a clockwise direction as far as Strand and in a net anti-clockwise direction between Strand and Gordon's Bay (Flemming 1982, Bartels and Schoonees 1987). Net quantities of sediment involved are not large and longshore sediment transport in the area is not generally regarded as a major coastal engineering problem at present. MSL and MHWS within the bay can be taken from the Simon's Town tide gauge and are at 0.16 m and 0.90 m elevation respectively relative to land levelling datum. HAT is at 1.24 m.

Development along the western shores is generally either high up and well above MHWS on the rocky shores or moderately well set back in the sandy bays. Almost the entire western seaboard under study is fronted by a coastal railway line set on rocks and embankments just above MHWS. During storms the line undergoes direct wave attack in places and in the past there have been problems associated with drift sands blowing from the beaches and blocking the line. On the northern shore, development takes the form of a number of low lying towns with limited protection and a main coast road which on occasions is currently overwashed on extremely high tides. The eastern seaboard has limited development on rocky shores and is not considered in this impact assessment.

Summarizing the physical environment (Table 3); the bay has a mixture of "hard" and soft coastlines, is exposed to most southerly swells and the prevailing southeasterly summer winds. The western seaboard is relatively sheltered from the direct action of southwesterly swells. Beaches are characteristically medium to fine grained and dissipative with much of the "soft" areas being moderately flat and low lying. Primary dunes are generally small and poorly developed and artificial dunes are currently being built in the Sunrise Beach area (Fig. 22). The area sustains a high population pressure with small town developments concentrated mostly on the "soft", low lying areas. Future development for the bay includes nodally developed recreational areas along the northern coast.

In this case study the impacts due a 1.0 m rise are first considered and the vulnerable locations are identified. To these locations rises of 0.5 m and 0.2 m are then applied.

4.2:1 Site Parameters

Like the other case studies it is assumed that the time required to establish the dynamic equilibrium of the new geomorphology is short compared to that required for sea level rise. Topography and bathymetry were taken from the S.A. Director of Survey and Mapping 1980, 1:10,000 orthophoto series and the 1987 S.A. Navy Hydrographer's 1:50,000 chart SAN 1016. An "average profile" is assumed and used in calculations.

Increased erosion is modelled by application of the Bruun Rule (1962) in its simplest form to the 12 profiles indicated on Fig. 20. Their location was chosen to highlight those areas most sensitive to coastal erosion.

The effect of increased flooding and inundation is modelled by adding the anticipated sea level rise to the existing water level. For example a 1 m rise in sea level will put MSL, MHWS and HAT at 1.16 m, 1.90 m and 2.24 m elevation relative to land levelling datum respectively. The assumption is made that land below these levels adjacent to the coast will flood if unprotected.

The effect of salt intrusion is modelled using the sea level rise/topography relationship described in chapter 3 above and the sea level rise is added to existing coastal water-tables to raise their levels. At present the salt water wedge extends less than 40 m into the Cape Flats Aquifer from the coast (Gerber, 1981). With a rise in sea level this intrusion is likely to stay within 40 m of the coastline in the absence of any major change in extraction rates. However, almost half of the Cape Flats area has an aquifer basal elevation below 0 m elevation (Gerber 1981). This area of aquifer has potential to be polluted if uncontrolled extraction takes place.

The effects of reduced protection from storm events is modelled as follows: Table 5 shows the design wave criteria for the location A to J shown in Fig. 20. If this table is representative of the whole bay it is not unreasonable to anticipate waves with significant height (H_s) of 4 m with return frequencies of the order of 10 years. Set up as a result of these waves breaking on the exposed sandy shore may be expected to be approximately 0.9 m (H_{max} = $1{\cdot}5H_s$, set up = 0.15 H_{max}, Shillington 1974). However, the presence of wide rocky ledges offshore, such as in the Strand-Gordon's Bay area, will tend to reduce this value due to waves breaking far offshore. Storm water levels measured on the Simon's Town gauge reach elevations of 1.2 m on more than an annual basis, 1.4 m more often than every 10 years and 1.5 m elevation every 100 to 150 years (Searson *in prep.*). A combination of set up and storm water level (which includes tide and shelf waves/surge components) is therefore capable of producing a water surface elevation at the shore of 2.4 m (1.5 m + 0.9 m) with return frequency of less than 100 years. Adding a 1 m rise in sea level suggests that coastal areas below 3.4 m elevation (1.0 m + 2.4 m) have potential to be flooded during these storms, possibly on a 40 to 50 year basis.

TABLE 5. Significant wave heights for False Bay at sites shown in Figure 20 (after Bartels and Schoonees 1987).

RETURN PERIOD	**SIGNIFICANT WAVE HEIGHTS (m)**									
	A	B	C	D	E	F	G	H	I	J
1	1.7	2.3	3.3	3.5	3.0	3.8	3.9	3.3	3.6	4.9
5	2.0	2.6	3.8	4.0	3.4	4.5	4.6	3.8	4.2	5.9
10	2.1	2.7	4.1	4.3	3.6	4.7	4.8	4.0	4.5	6.3
15	2.1	2.8	4.2	4.4	3.8	4.9	5.0	4.1	4.6	6.6
20	2.1	2.9	4.3	4.6	3.8	5.0	5.1	4.2	4.7	6.7
50	2.3	3.0	4.7	4.9	4.1	5.4	5.5	4.5	5.4	7.7
100	2.4	3.2	4.9	5.1	4.3	5.6	5.8	4.7	5.4	7.7

4.2:2 Results

Table 6 shows the calculated recession of the shoreline from application of the Bruun Rule (1962).

TABLE 6. Coastal recession in metres for False Bay as indicated by the Bruun Rule (after Hughes and Brundrit 1991c). Sites shown in Figure 20.

		EROSION (m)	
PROFILE	**1.0 m Rise**	**0.5 m RISE**	**0.2 m RISE**
1	48	24	10
2	70	35	14
3	70	35	14
4	66	33	13
5	102	51	20
6	97	49	20
7	105	53	20
8	120	60	30
9	70	35	14
10	145	73	29
11	150	75	30
12	130	65	26

Figs. 21 to 25 show the predicted position of the new MHWS and 1.5 m storm flood levels after a rise in sea level of 1 m. A glance at each figure is sufficient to gain an overall impression that a 1 m rise is enough to have a considerable detrimental impact. The combined impacts of sea level rise are considered for those locations vulnerable to a 1 m rise:

Glencairn: - section 1. 48 m of erosion will put the new MHWS at the base of the railway embankment allowing direct wave impingement with obvious consequence for the railway and road behind.

Fish Hoek: - Fig. 21. $\pm$ 70 m of erosion will remove recreational development, beach cafes and car park on the south side and leave the railway line within 25 m of MHWS.

The 40 to 50 year storm with shore water levels 1.5 m above MHWS would cover the beach front development, car park, yacht club and probably the railway station.

Note the hatched areas in Fig. 21. These indicate the areas where the water-table is currently within 50 cm of the surface (S. Cumming, Assist. Town Eng. Fish Hoek. Pers. Com. 1989). A 1 m rise in the water-table accompanying a 1 m rise in sea level will probably cause waterlogging and engineering problems in these areas and their areal extent is likely to increase significantly. Both of these zones contain residential properties. Freshwater supplies are not derived from the local aquifer and consequently salt pollution is unlikely to be a problem.

Muizenberg/Sandvlei: Fig. 22. Coastal erosion of $\pm$100 m will put the MHWS well behind the first block of property on the west side of Muizenberg.

Storms and their associated surges and set-ups are usually of sufficient duration to allow considerable penetration into most inlets. Due to the low lying nature of the surrounding areas, a large area of residential development is potentially vulnerable to flooding by a 1.5 m storm as can be seen from the figure.

Sandvlei and the Marina da Gama housing development have a water level maintained at an optimum level between 0.86 m and 1.06 m elevation and grassed embankments and lawns extend right down to the water's edge. Retaining walls have an approximate maximum elevation of 1.1 m. With the new MHWS in the open sea at 1.9 m after a 1 m rise, the vlei and surrounds have a high potential for flooding and inundation at high tide. Even the new MSL at 1.16 m will be above the vlei's optimum level. The mouth of the vlei is canalized and without detailed surveys and a knowledge of the competence of the structure, predictions of the tidal range within the vlei is difficult. But no matter how restrictive the mouth

is, unless totally closed, some flooding and inundation of properties will happen with tidal levels above MSL.
Under normal conditions, the Sandvlei will change from a freshwater dominated system to a salt water system with obvious ecological consequences and a probable improvement in the general "healthiness" of the vlei.

Zeekoevlei: Fig. 23. The predicted 105 m of erosion will be sufficient to seriously damage the Cape Flats Wastewater Treatment works, putting the new MHWS approximately 70 m landward of the Baden Powell Drive, the main coastal road.
The impact of a large sea storm in this area will be severe as even at present, moderately sized storms wash over and cause damage to the road at high tide.

Strand: Fig. 24. This 150 m of erosion ignores the presence of the sea wall backing the beach and assumes that the development landward of this wall is built on erodible substrate. However, this amount of erosion is likely to be an over-estimate due to the presence of offshore rocky ledges preventing the maintenance of an equilibrium sandy profile. In the event that the wall holds, the beach in front of the wall will be lowered, and MHWS and HAT will be within 0.8 m and 0.4 m of overtopping the wall at about 2.7 m elevation. Even slight wave action at high tide will produce overtopping and a 1.5 m storm water level will cause serious problems.

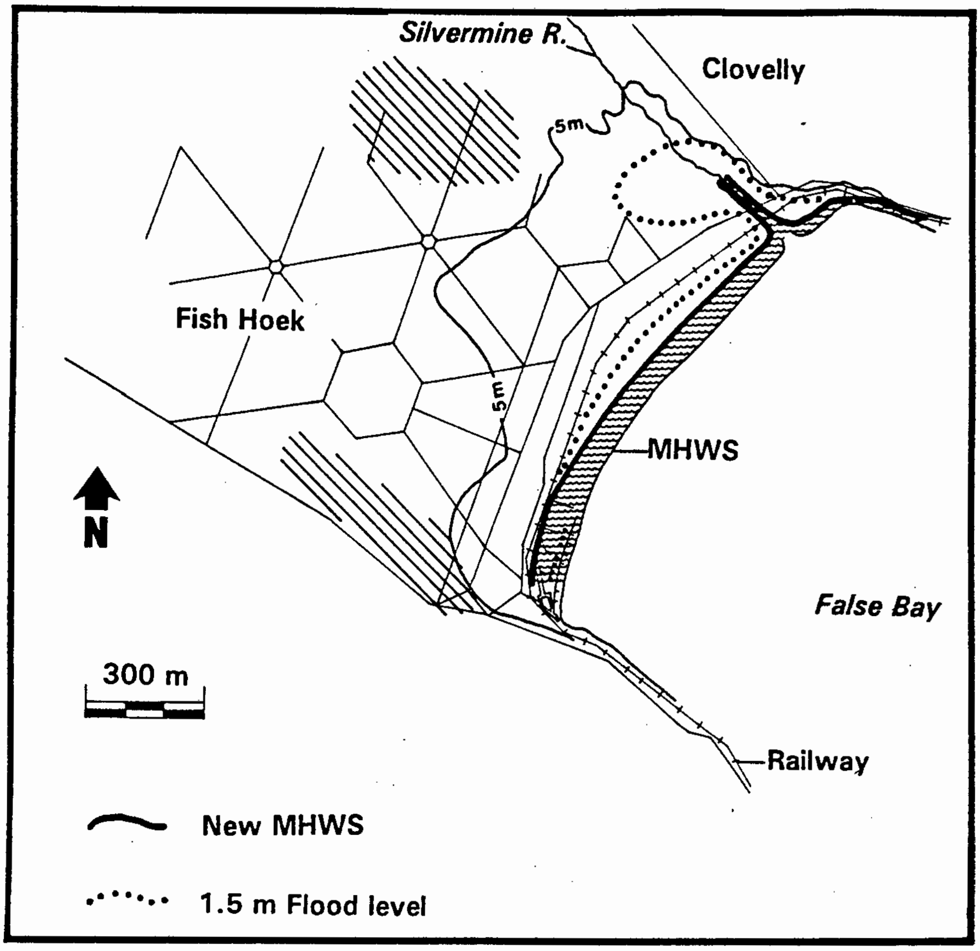


FIGURE 21. Fish Hoek:- Position of new MHWS and 1.5 m flood level after a rise in sea level of 1 m. Erosion of between 65 m and 70 m is likely to put MHWS within 25 m and 50 m of the railway line on south and north ends of the bay respectively. Holiday chalets in the mid-beach area will probably be covered by the transgressing dunes and the area landward of the Silvermine river mouth will be flooded at HAT. The hatching represents areas where the water-table in within 50 cm of the surface at present (after Hughes and Brundrit, 1991c).

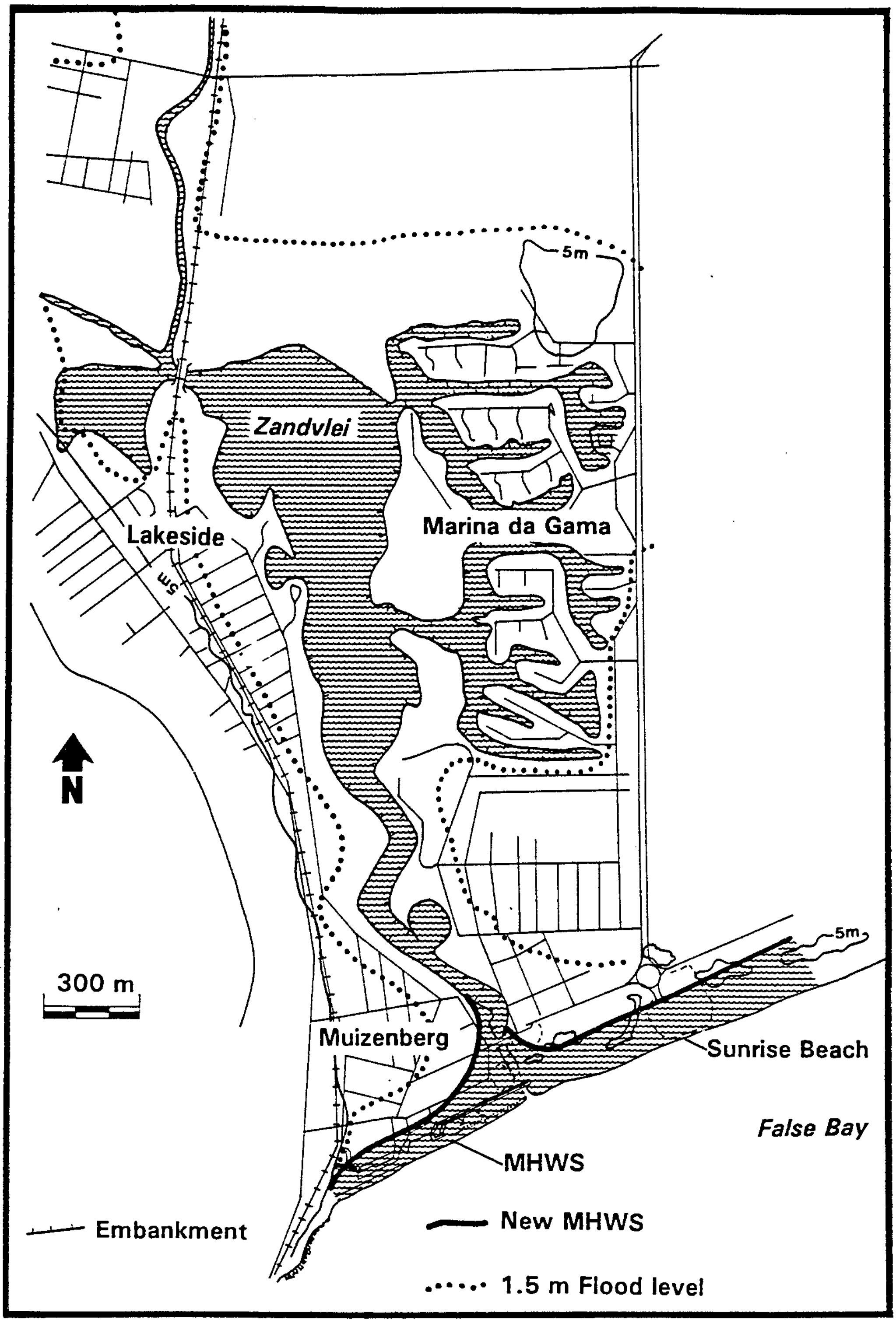


FIGURE 22. Muizenberg/Sandvlei:- Position of new MHWS and 1.5 m flood level after a rise in sea level of 1 m. Approximately 100 m of coastal erosion predicted. Beach Rd. to the east of Sandvlei will be within 0.8 m elevation of MHWS. Note the large area susceptible to storm flooding (after Hughes and Brundrit 1991c).

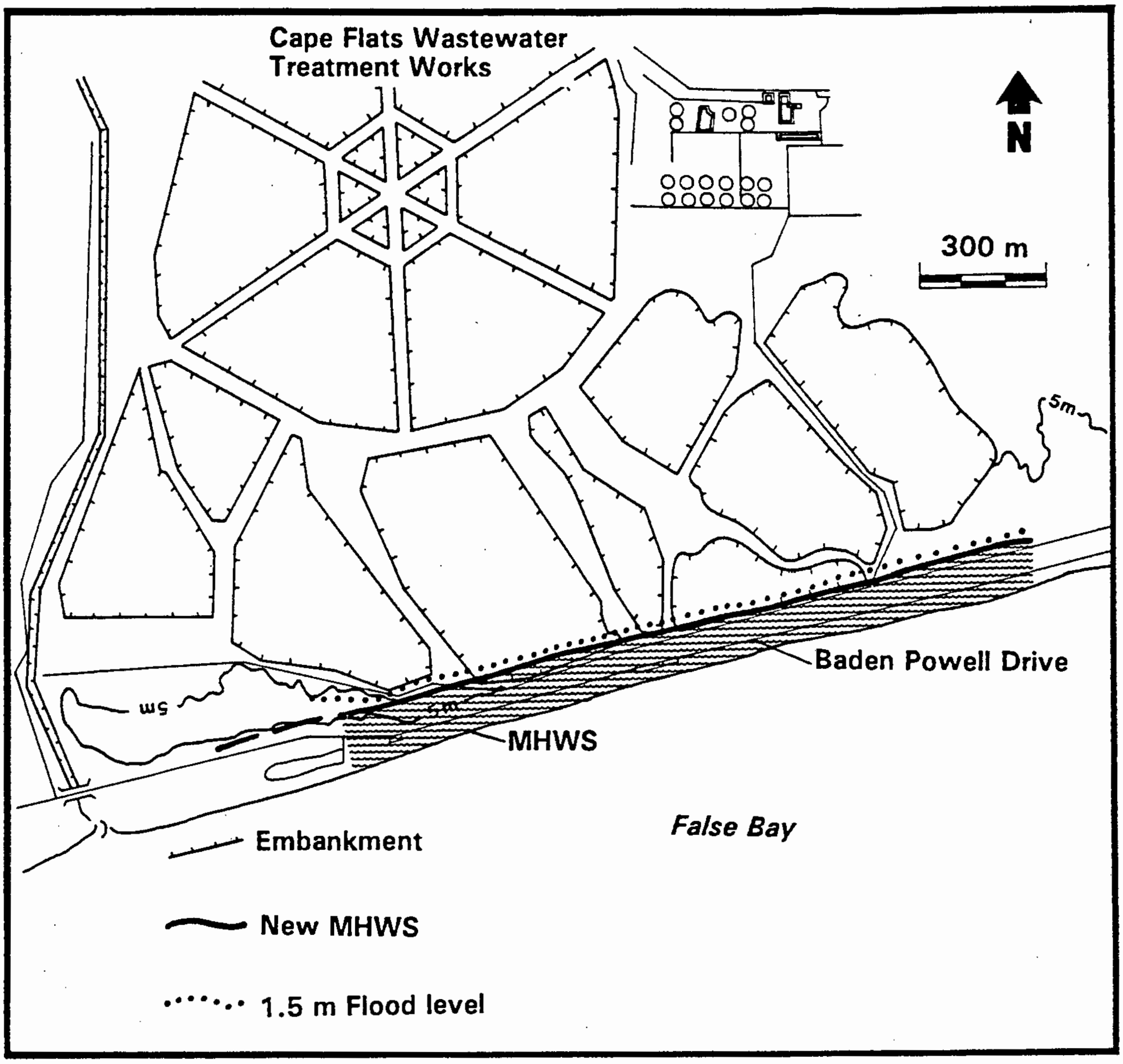


FIGURE 23. Zeekoevlei:- Position of new MHWS and 1.5 m flood level after a rise in sea level of 1 m. The predicted MHWS will be approximately 70 m landward of the Baden Powell Drive - i.e. within the position now occupied by the waste water maturation ponds (after Hughes and Brundrit 1991c).

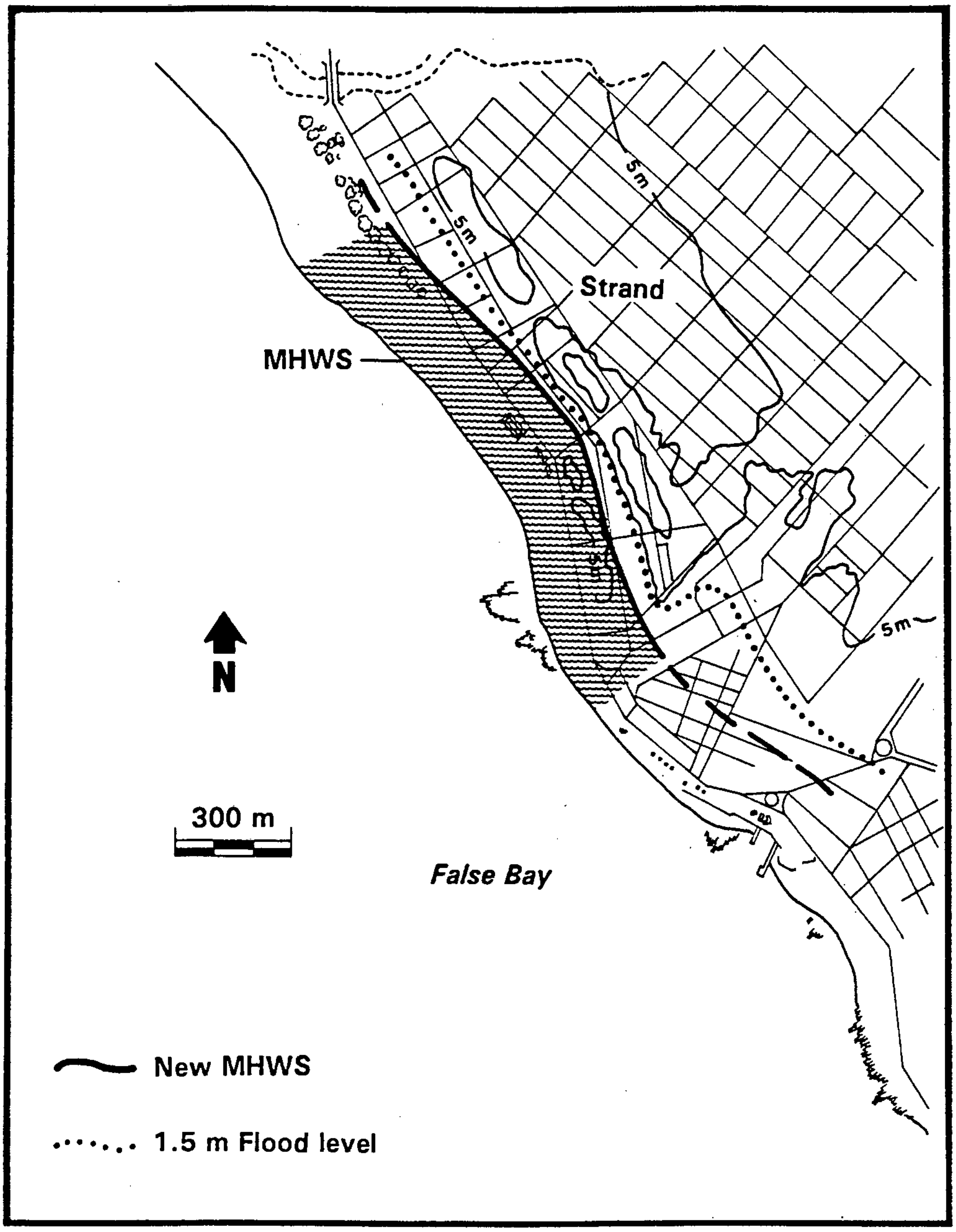


FIGURE 24. Strand:- Position of new MHWS and 1.5 m flood level after a rise in sea level of 1 m. The location of the new equilibrium MHWS 150 m, assuming adequate thickness of sediment to allow erosion, will effectively remove the entire first block of beachfront development along the entire front of Strand (after Hughes and Brundrit 1991c).

Gordon's Bay: Fig. 25. Like the modelled erosion for Strand, assumptions are made which probably over-estimate the rate. If the sea wall is sufficiently competent and does hold, then HAT and MHWS will be within 1.5 m and 1.8 m respectively of overtopping the wall. The beach will be lowered, probably removing all the sandy part, and the wall will be significantly overtopped during a 1.5 m storm event.

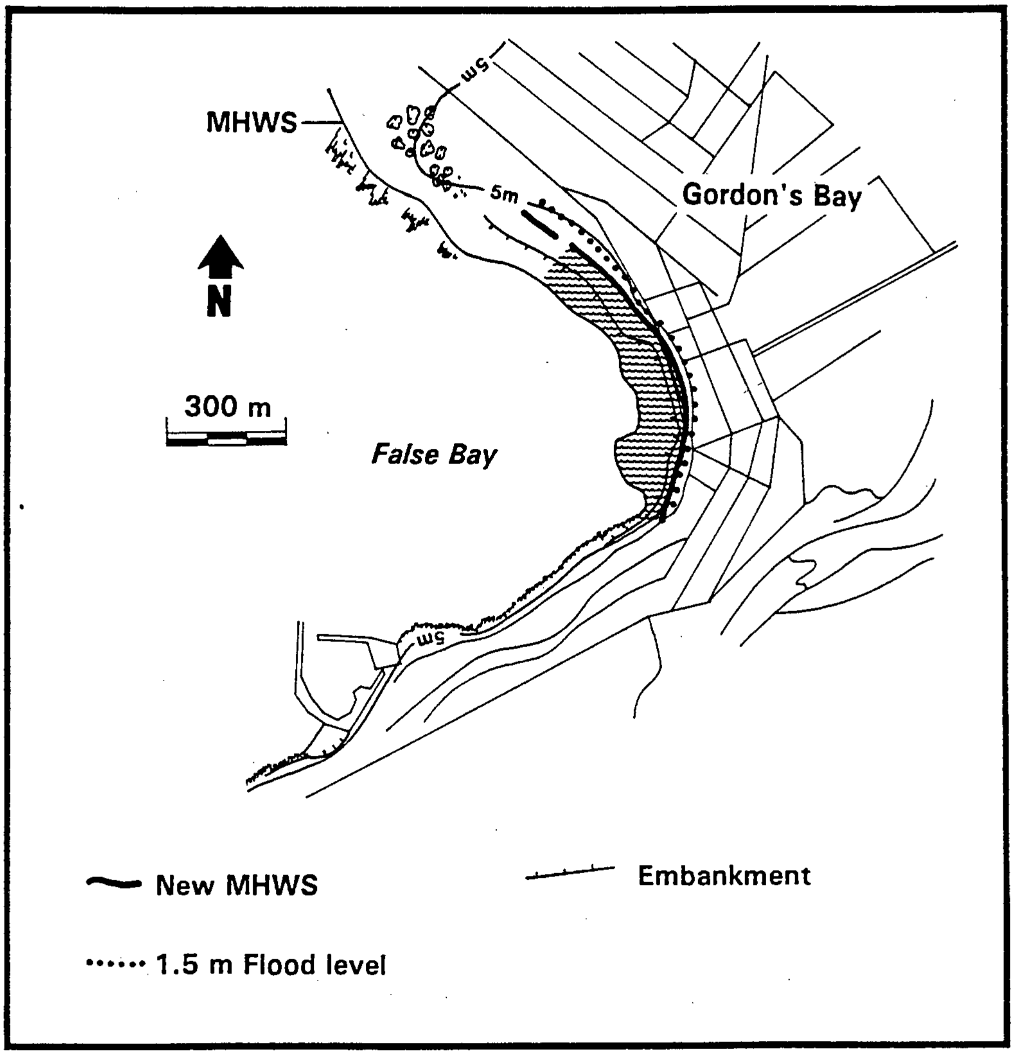


FIGURE 25. Gordon's Bay:- Position of new MHWS and 1.5 m flood level after a rise in sea level of 1 m. The new equilibrium MHWS position will be approximately 45 m landward of the beach-top road (after Hughes and Brundrit 1991c).

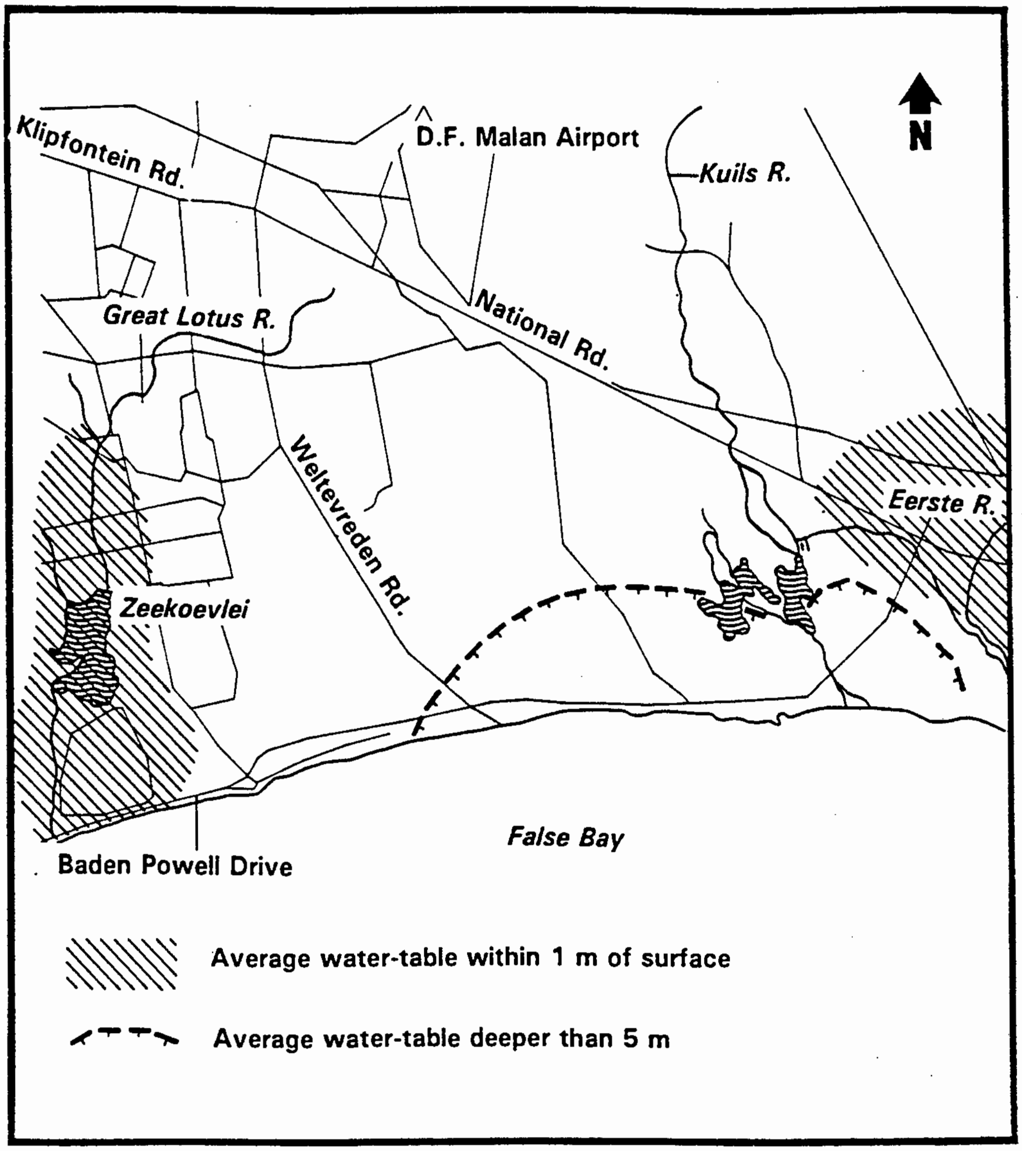


FIGURE 26. Areas of the Cape Flats with high water-tables, susceptible to future waterlogging. Note that at certain periods, large sections of these areas are currently waterlogged (after Hughes and Brundrit 1991c).

Figure 26 shows areas of the Cape Flats susceptible to waterlogging due to elevated groundwater levels. Within the hatched areas the water-table is currently within 1 m of the surface (Hughes and Brundrit, 1991c). Raising the water-table by 1 m will cause waterlogging and flooding in large areas of Zeekoevlei and Mitchells Plain and parts of Khayelitsha.

Salt intrusion into the Cape Flats Aquifer currently extends some 40 m from the shoreline and a similar order of intrusion is expected at the new shoreline (Hughes and Brundrit 1991c). However, the future groundwater tables and rates of salt water intrusion are more likely to reflect freshwater extraction rates within the aquifer then any change in sea level.

4.2:3 Discussion

The results of application of the Bruun Rule (1962) show a wide range of potential coastal erosion. This is predominantly a function of the offshore bathymetry with the gentler offshore gradients allowing greater shoreline recession. Even though these results may only be used as a guideline, it is clear that the erosion sustained by a 1 m rise and the potential for storm damage at unacceptable frequencies will seriously affect the whole of the coastline and disrupt lifestyles in all the developed areas. The effects of raised water-tables would seem very severe for a 1 m rise but these effects can be reduced by freshwater extraction and dewatering programs. Projected freshwater extraction rates for this area are unknown, but it is likely that the population pressure and land demand will facilitate the lowering of the water-table.

Repeating the whole modelling exercise for a 0.5 m rise refines those areas of impact. Table 6 shows the values of erosion expected on profiles 1 to 12 for a 0.5 m rise in sea level.

Glencairn will not be seriously affected by 0.5 m rise and neither will Strand and Gordon's Bay. However the beach profile will be significantly lowered at Strand and Gordon's Bay, with the possible risk of losing the sandy beach altogether, putting the MHWS against the sea walls. Muizenberg and Fish Hoek will have a marginal amount of damage with the new MHWS being just landward of the beach top, in areas now occupied by car parks and poorly developed foredunes.

The effect of a raised water-table comparable to the 50 cm sea level rise will be sufficient to cause serious engineering problems in those Fish Hoek areas outlined in Fig. 21, but these problems may be controlled (at a cost) by dewatering schemes.

The effect of 1.5 m storm events will be slightly reduced in Fish Hoek and of little consequence but the effects of flooding, inundation and storms in Sandvlei will be serious. With a 0.5 m rise, MSL and MHWS in open water will become 0.66 m and 1.40 m elevation respectively -

i.e. the open water MHWS value will be above the elevation of retaining wall (1.1 m) protecting the Marine da Gama development. The restrictive effect of the mouth is not likely to be sufficient to cause such a drastic reduction in tidal range in the vlei down to "safe" levels and parts of Marine da Gama and areas surrounding the vlei will surely be flooded and inundated at high tides.
The effect of erosion in the Zeekoevlei area will be sufficient to erode the main coast road.

For a 0.2 m rise the effects of increased erosion in the Zeekoevlei area (Table 6) will still be considerable and will probably be enough to put the road at risk to storm damage from relatively small storms.
The Sandvlei/Marina da Gama area will also have cause for concern in the event of a 1.5 m storm event. Water levels on the shore may reach 2.6 m elevation (2.4 m + 0.2 m) and some of this storm will penetrate into the inlet. The risk exists even today although the presence of a wider beach and well maintained weir at the mouth tend to reduce the risk.

In summary, this exposed, low lying, soft coastline with development close to the sandy beaches in many places, is vulnerable to sea level rise through all four categories of risk. A 1 m rise will have serious consequences for the whole coastline. A 0.5 m rise will be of consequence in the Fish Hoek, Muizenberg/Sandvlei and Zeekoevlei areas in terms of increased erosion, storm flooding and groundwater flooding. Even a 0.2 m rise will be sufficient to damage the Baden Powell Drive - i.e. the main coast road, and Marina da Gama during major storms.

The impacts of groundwater flooding may be reduced by proper aquifer management but the erosion and storm damage problems are less easy to manage. After only a small rise in sea level, both Marina da Gama/Sandvlei and the Zeekoevlei coast will become extremely vulnerable to storm damage. A larger rise will cause loss of beach where those beaches are topped by hard defences or loss of roads, recreational and car parking facilities in locations where those defences do not exist. Potential storm damage at the 0.5 m rise stage becomes critical to the whole bay. At this point, beachside development around the perimeter of the bay will have a limited usefulness. A 1 m rise will effectively change the pattern of use of the whole bay.

Note that the effect of storm induced erosion has not been modelled for the False Bay coastline but an additional 20 m of shore erosion would not be unreasonable to anticipate during a large storm. This order of magnitude of freeboard above MHWS must be considered for all stages of sea level rise and must be thought of as a very conservative estimate. In addition it is expected that large storm waves may produce significant over-topping of the low rocky sections of the coast. Development on these hard sections may not be entirely safe from sea level rise and wave over-topping modeling should be carried to evaluate the risk to such infrastructure as the coastal railway line.

The lessons to be learnt from this case study may be listed:

- highly developed open coasts are generally vulnerable to increased erosion and storm damage;

- developed tidal inlets in open coasts are exceedingly vulnerable to storm flooding as a result elevated coastal water levels due to storm surges and wave set up;

- ribbon development (e.g. coast roads) close to the shoreline is to be avoided wherever possible. Its length increases its vulnerability and reduces its manageability in a "long supply line" analogy;

- where development tops a beach, that development must either be fronted by low cost /expendable development or preferably dunes/buffer zones to allow for erosion and storm damage. Alternatively, the development must be protected by nourishment or hard engineering structures in which case a lowering of the beach profile and associated changes in beach characteristics, must be expected;

- where sufficient freshwater flow in aquifers is available the effects of salt pollution and raised water-tables may be ameliorated by existing aquifer and water-table management techniques.

4.3 The Impacts of Sea Level Rise on Durban

The Durban beachfront (Fig. 27) is essentially an unconsolidated sandy shoreline backed in most places by significant development and infrastructure immediately landward of the beach. A retaining/beach wall is present along much of the southern section of the study area. The dominant swell direction is from the south and northwards longshore transport of sediment necessitates significant beach nourishment. Annual rates of sediment loss for the Durban seafront vary between 0 and 300,000 m^3/year (CSIR 1988b). The Umgeni river's average contribution to the sediment budget is unknown and although the general transport direction is northwards, away from the study area, under extreme conditions some fluvial sediment is deposited to the south. The presence of an underwater dump located in an area east of the harbour mouth by years of dumping Cave Rock material, tends to focus wave energy around the Central and North Beach areas leading to sharp variations in longshore transport potential. Small changes in the incident wave conditions can alter the wave energy foci and cause significant variations in rates of sediment transport (CSIR 1989a). "Average" longshore transport rates may therefore be used only with great caution. Alteration of the natural equilibrium profile also makes application of coastal erosion rules tenuous.

Current mean sea level for the Durban area is 0.2 m elevation relative to Land Levelling Datum with MHWS and HAT at 1.06 and 1.40 m respectively.

Detailed groundwater studies for Durban are unavailable but groundwater levels in parts of the Central Business District, areas near the foreshore and behind the upmarket hotel area on the seafront are known to be within approximately 1 m of the surface and engineering difficulties have been encountered in the past (Prof. T. Mason, Univ. of Natal, *Pers Comm* 1990). The definition of these areas is vague and only their general location is indicated in Figure 27.

Design wave criteria based on 3 years of wave rider buoy data in 12 m of water (CSIR 1988b) indicate a 1 in 100 year type significant wave height to be 5 m. Taking this storm wave prediction as being representative of the whole bay and applying standard engineering techniques (SPM 1984), wave set up of the order of 0.8 m may reasonably be expected from 5.4 m deep water waves on a 1:30 beach slope. Alternatively, the assumption may be made that the 5 m wave in 12 m of water is actually breaking and the set-up may be calculated to be 0.9 m (set-up = $0.15H_{max}$ where H_b is assumed equal to H_{max}). In the light of the uncertainty regarding future sediment dynamics and the limits of resolution of erosional models, the latter more approximate method is preferred. The similarity between the results obtained by the two methods is noteworthy. However, based on examination of wave records from other nearby sites in Natal, it is felt that a 1 in 100 year return period for a 5 m wave is excessively long and the actual return period may be closer to 1 in 10 years. Storm surge from a large storm may reasonably be expected to exceed 0.5 m and therefore a combination of surge and set up is capable of producing a shore water level 1.4 m above its mean sea level.

This section summarizes the findings of three sea level scenarios (Hughes and Brundrit 1990); a 0.5 m and 1.0 m rise assuming a continuation of usual beach nourishment procedures and a 1.0 m rise assuming cessation of nourishment and achievement of complete rise by 2075.

4.3:1 Site Parameters

Increased coastal erosion is modelled using the Bruun Rule (1962) with an extension to account for an "average" rate of sediment depletion along the shore (equation 5, C3.1:1).

The average rate of depletion was taken to be 12,000 m^3/km/year (CSIR 1989a) and the rule was applied to the 9 sections shown in Figure 27. Topography was taken from the 1981 1:10,000 orthophoto series and the vertical resolution was improved by using 1988 aerial photography and a Topocart photogrammetry machine. Bathymetry was taken from the 1989 S.A. Naval Hydrographer's 1:25,000 SAN chart 1030 and previous hydrographic surveys (CSIR 1988b) and an "average" profile is assumed.

Where possible, calculation of the run-up and overtopping of seawalls is carried using standard engineering techniques (SPM 1984c) assuming smooth vertical walls. Although the actual use of this type of wall is most probably impractical, its inclusion in this case study is intended to illustrate the importance of the "reduced protection from extreme events" impact category.

Flooding and inundation is modelled by adding the rise in sea level to the existing sea level. The effects of raised water-tables is modelled by the addition of the rise in sea level to the elevation of the existing water-table, however, this is an over-simplification and does not consider any changes in future freshwater extraction rates which may occur. The extent of salt water intrusion and pollution of the coastal sediment and Umgeni estuary is a function of freshwater flow rates, piezometric and river bottom gradients, all of which are poorly understood. These effects are therefore not modelled although it is felt their impact will be very small in this area.

The effect of increased storm flooding and damage is modelled by the addition of the surge and set up of a "large return period" storm (i.e. 0.5 m + 0.9 m) to the new water level. Storm induced erosion has not been modelled for the Durban coastline but a conservative estimate of 20 m would be reasonable to anticipate for a large storm. This amount should be borne in mind for all stages of sea level rise.

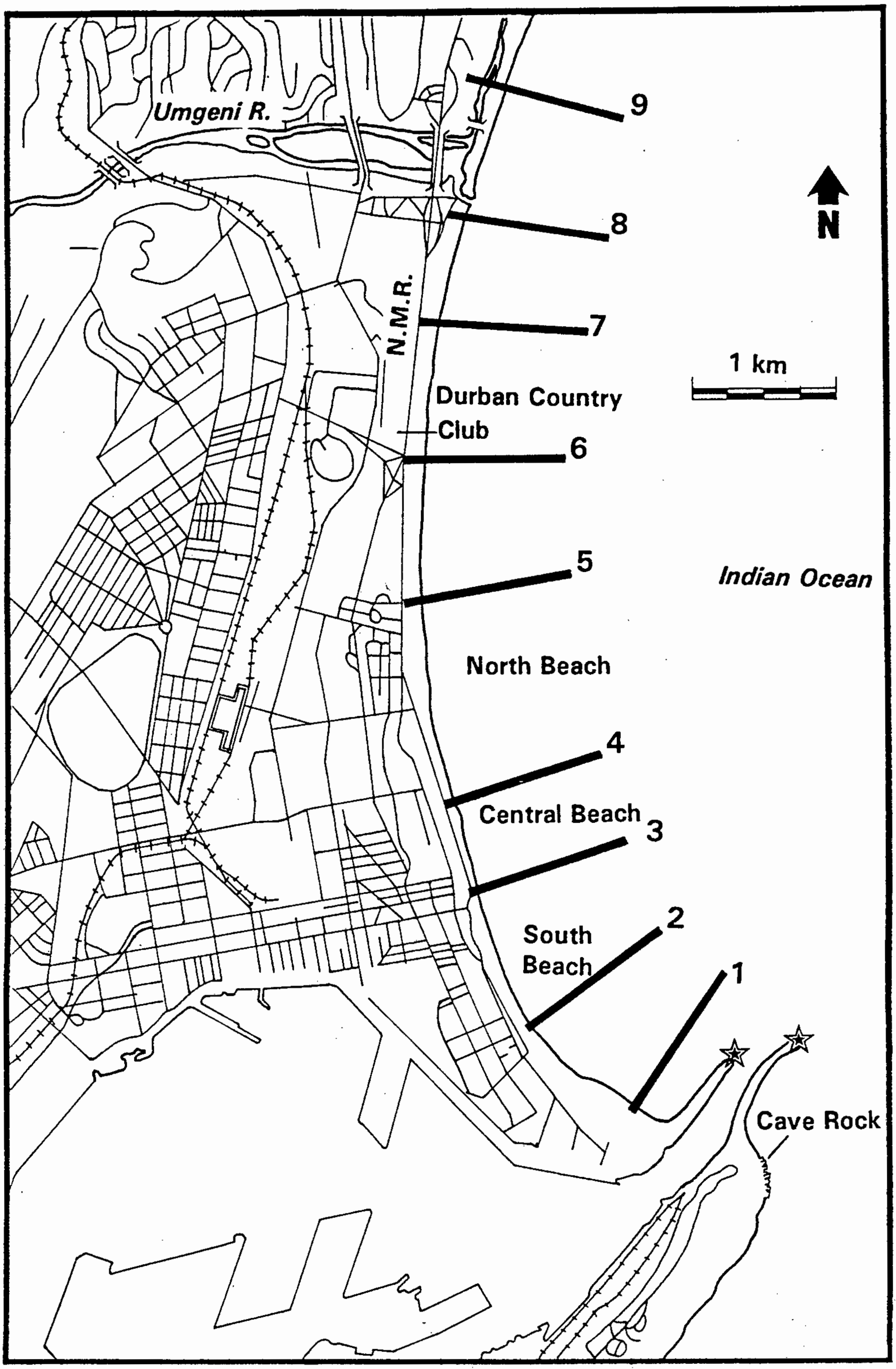


FIGURE 27. Durban beachfront study area and location of 9 profiles to which the Bruun Rule was applied (after Hughes and Brundrit 1990b).

4.3:2 Results

Table 7 shows the calculated shoreline recession for the 9 profiles shown in Fig. 27 under the three sea level scenarios:

1. 1.0 m rise by 2075 with no beach nourishment.

2. 1.0 m rise with beach nourishment

3. 0.5 m rise with beach nourishment

These scenarios assume that the beach profile has shifted landward and upwards and the shore protection is ineffective at stopping the erosion or profile migration.

TABLE 7. Coastal recession in metres for Durban as indicated by the Bruun Rule. Profile locations shown in Figure 27 and average beach nourishment rate taken as 12,000 m^3/km/year.

PROFILE	**1.0 m RISE** WITH NO NOURISHMENT	**1.0 m RISE** WITH NOURISHMENT	**0.5 m RISE** WITH NOURISHMENT
1	130	90	46
2	110	76	38
3	113	77	38
4	137	99	49
5	95	64	32
6	109	68	34
7	92	52	26
8	102	60	30
9	114	68	34

Under scenario 1, the entire beachfront will be displaced and eroded up to over 100 m landward of the existing developed margin. Under scenario 2.

most of the coastline would be eroded landward of the current development and under scenario 3, loss of developments and infrastructure will occur on the southern end of the study area. Clearly, with the amount of capital investment involved, shoreline recessions of this magnitude will not be allowed to occur and strengthening of the sea defences will probably take place. The difference between scenarios 1 and 2 indicates the importance of longshore sediment transport and beach nourishment in this location. Discontinuation of the nourishment is unlikely ever to occur and scenario 1 is therefore dropped from further investigation.

In the case of a wall stopping migration of the profile by retaining sand from being drawn from the subaerial portion of the profile, there must be a volumetric balance seaward of the sea wall. The partial migration of the profile combined with this balance effectively lowers the beach in front of the wall as shown in Fig. 28. Consequently, existing walls may have to have their foundations deepened to counter this lowering and, their heights raised to counter overtopping by higher water levels. Application of a non-dimensions method (Dean & Maurmeyer 1983) suggests that for a 1 m rise this mass balance will account for a 0.2 m to 0.4 m lowering at the toe of the wall. However, this amount of lowering is beyond the limit of resolution of this study and is therefore not considered in detail. Beach lowering as a result of profile translocation only is considered.

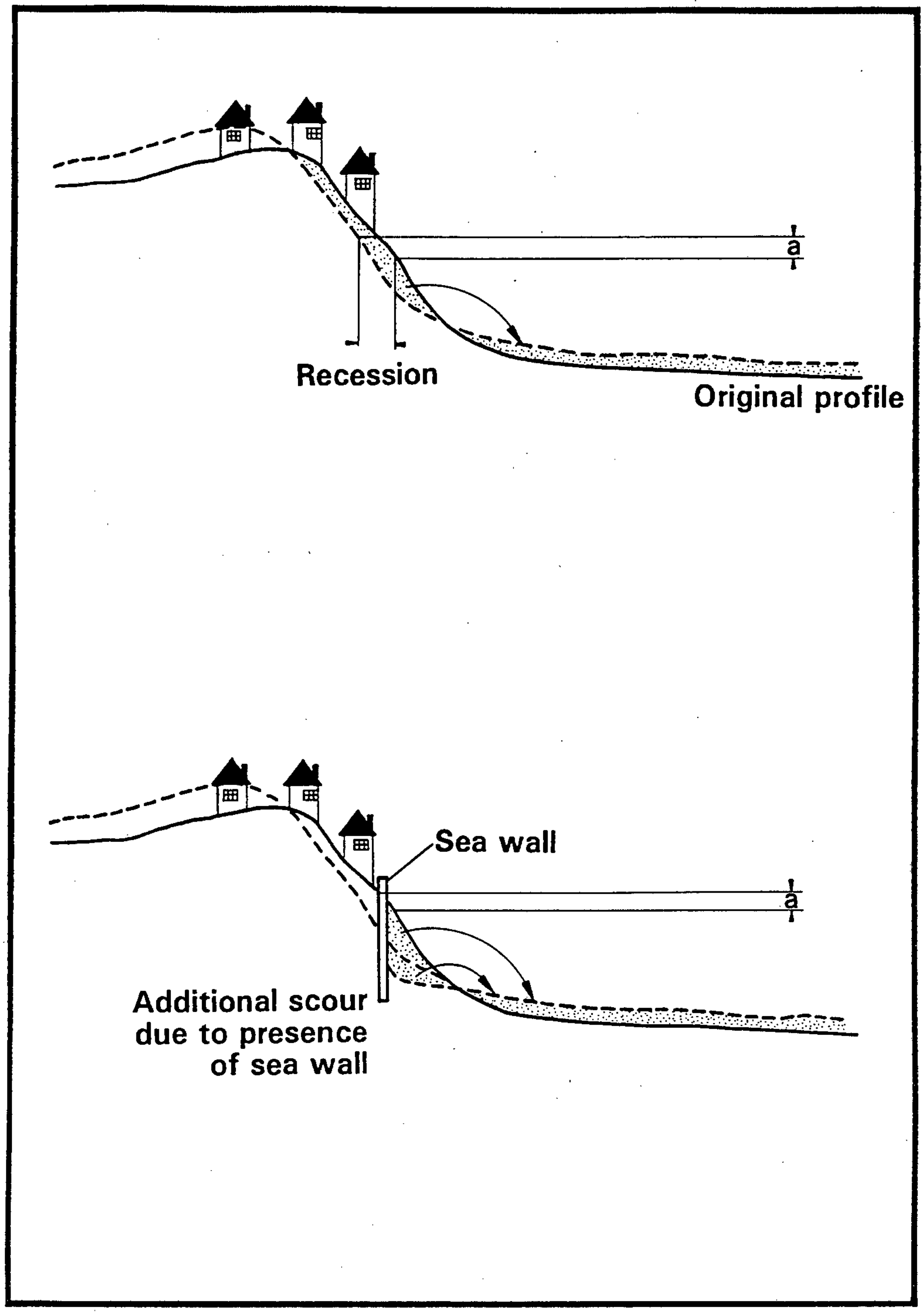


FIGURE 28. Effects of a sea wall on the migration of a beach profile. (A) Normal profile migration. (B) Arrested profile migration showing volumetric sediment balance seaward of the wall, lowering the profile (after Hughes and Brundrit 1990).

TABLE 8. Beach elevations, run-up and overtopping for Durban, assuming present rates of beach nourishment.

1.0 m RISE

PROFILE	PLAN DISTANCE FROM BEACH TOP TO MHWS	MHWS ELEV.	BERM ELEV.	STORM ELEV.	MAX. SFL DEPTH AT WALL	WALL TOE ELEV.	DEVEL. ELEV.	WALL HEIGHT	RETAINING OR SEA WALL	RUN-UP ELEV. (RUN-UP + SFL)	OVERTOPPING RATE ($m^3s^{-1}m^{-1}$)
1	0	2.06	1.2	3.5	2.3	-0.6	8.2	8.8	SW	9.9	0.05
2	0	2.06	0	3.5	3.5	-2.7	4.4	7.1	SW	13.2	3.5
3	0	2.06	1.5	3.5	2.0	-0.1	4.2	4.3	SW	9.3	2.4
4	0	2.06	0.4	3.5	3.1	-2.0	3.2	5.7	SW	12.5	100%
5	45	2.06	3.7	3.5		3.7	9.5	5.8	R		
6	0	2.06	1.7	3.5	1.8	0.3	6.0	5.7	SW	9.3	0.7
7	40	2.06	6.7	3.5		6.7	8.4	1.7	R		
8.	65	2.06	≈5	3.5							
9	140	2.06	>SFL	3.5							

0.5 m RISE

PROFILE	PLAN DISTANCE FROM BEACH TOP TO MHWS	MHWS ELEV.	BERM ELEV.	STORM ELEV.	MAX. SFL DEPTH AT WALL	WALL TOE ELEV.	DEVEL. ELEV.	WALL HEIGHT	RETAINING OR SEA WALL	RUN-UP ELEV. (RUN-UP + SFL)	OVERTOPPING RATE ($m^3s^{-1}m^{-1}$)
1	45	1.56	4.7	3.0		4.7	8.2	3.5	R		
2	0	1.56	0.5	3.0	2.5	-1.4	4.4	5.8	SW	9.5	1.4
3	40	1.56	2.9	3.0		2.9	4.2	1.3	R		
4	0	1.56	0.5	3.0	2.5	-1.4	3.2	4.6	SW	10.1	3.6
5	85	1.56	8.3	3.0		8.3	9.6	1.3	R		
6	40	1.56	2.9	3.0		2.9	6.0	3.1	R		
7	80	1.56	8.4	3.0							
8	110	1.56	3.0	3.0							
9	175	1.56	>SFL	3.0							

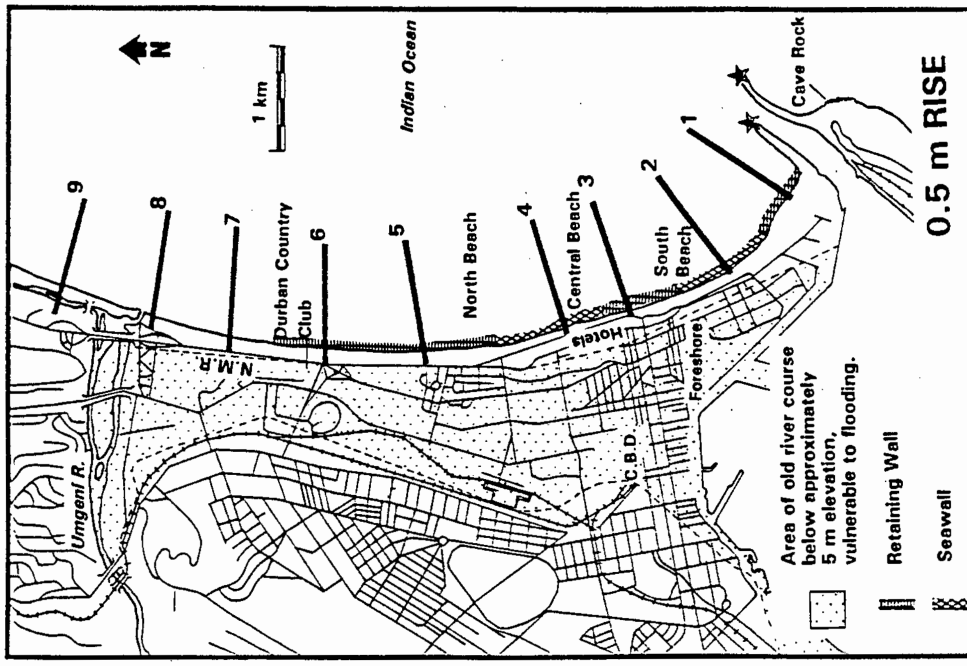
SFL = Storm Flood Level

In addition short term scouring of the toe of the wall may occur during wave action. The depth of this scour is approximately equal to the largest unbroken wave that can exist in that depth of water (SPM 1984d). In this case the scour may be of the order of several meters deep.

From the results given in Table 7 and scale drawings for scenarios 2 and 3, it is possible to calculate the horizontal distance between the retaining wall and MHWS and the minimum height of retaining wall necessary to counter the effects of profile lowering and toe scour in a large storm. The rate at which a sea wall of present maximum elevation would be overtopped during that storm may also be found (SPM 1984c). The results are displayed in Table 8 and Figure 29.

Under the 1 m rise scenario the entire coastline will be seriously affected by coastal erosion. Overall, some 7 km of coastline from the harbour mouth to north of the Country Club (Fig. 29) will require some form of protection or retaining wall due to the lowering of the beach profile. Sea defences will be required to protect existing development between locations 1 and 4 (Fig. 29), and around location 6 where the beach will effectively disappear completely, and MHWS will be adjacent to the wall.
Without increasing the height of the seawalls to provide additional protection from storms these walls will have to be up to 9 m high and even so severe overtopping will occur. In the region of profile 4 the storm flood level is 0.4 m above the level of existing development and elsewhere rates of overtopping may be up to 3.5 $m^3/s/m$. Retaining walls will be required in locations 5 and 7 to cater for the lowered beach profile.

The impact of flooding, inundation and salt water intrusion will be slight although an increase in the tidal prism of the Umgeni estuary will be noticeable along with an associated increase in tidal currents. The mouth area is undeveloped and changes in exit dimensions (if any) or mouth migration will have little significant impact. Elevated groundwater tables in the central business district (CBD) are likely to cause and exacerbate existing engineering problems and difficulties with underground services. Areas likely to be affected (but not yet possible to define accurately) include the upmarket tourist hotels on the seafront and behind.



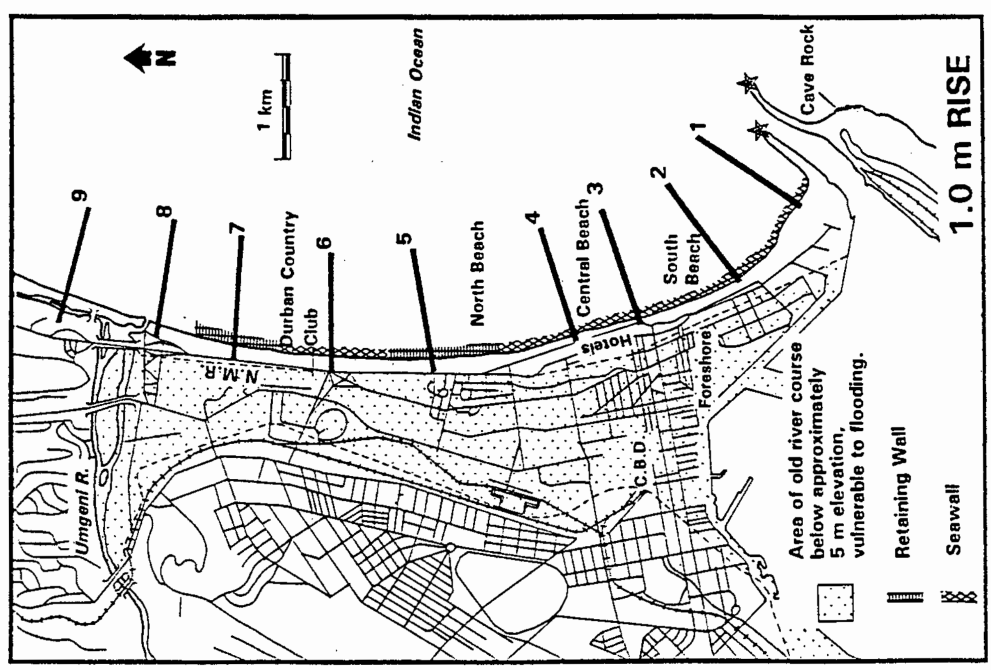


FIGURE 29. Durban's shore protection requirements and area of old river course below approximately 5 m elevation.

The problems of extreme events are more serious. The occurrence of either a 1:100 year Umgeni river flood and a high spring tide or a "large" (1:10 to 1:100 year) sea storm with no river flow will be sufficient to raise the water level in the Umgeni estuary to $\pm$ 3.5 m elevation. This level would be sufficient to break the river's banks and flood the most part of the CBD via the golf course, railway lines and NMR road (i.e. down the old river course) if flood prevention measures are not taken. River and sea storm combinations will likewise have serious consequences. Figure 29 shows the approximate location of the old river course and floodplain through the city below 5 m elevation. The river used to enter the sea within the area now occupied by the harbour. A large portion of this area would be vulnerable to such extreme events.
This type of river mouth is typical of this part of the coast where rates of longshore sediment transport are high. The river mouth is deflected updrift until eventually the river runs parallel to the shore, separated from it by a narrow spit and dune barrier. River floods or storm washover action often break through the barrier, shortening the length of the spit and river mouth by abandoning the old channel.

Clearly a 1.0 m rise in sea level at Durban would have disastrous erosional and storm damage consequences for the whole area.

Under the 0.5 m rise scenario with beach nourishment, almost the entire length of coastline from the harbour mouth to the north of the Country Club Beach will be seriously affected by increased coastal erosion. To the north of the Country Club, the impacts will be less severe as the beach is wider and the foreshore less developed. Table 8 and Figure 29 summarizes the impacts of increased erosion. In most cases the beach profile will be lowered landward of the development. In front of profiles 2 and 4, the beach will be sufficiently lowered to allow the new MHWS to reach the wall. Sea walls in these areas would need to be up to 6 m high and during a "large" storm could be overtopped at rates of up to 4 $m^3/s/m$. Retaining walls would be required elsewhere up to 3.5 m high and may be subject to wave attack during extreme storms.

Inundation, flooding and salt pollution will have little impact except for the mangrove community at Beechwood Creek which will require a freshwater flux. Elevated groundwater tables will exacerbate engineering problems in the same important economic zone as for the 1 m rise. The coincidence of a 1 in 100 year Umgeni flood and a large sea storm could put water levels up to 4.5 m elevation in the estuary almost certainly flooding the most part of the CBD (Fig. 29).

A 0.2 m rise in sea level would have a limited effect on Durban except for a slight reduction in beach width.

4.3:3 Discussion

Beaches in an exposed environment, backed by hard development are exceedingly vulnerable to changes in sea level and increased erosion. In this case a rise of only 0.5 m will be sufficient to "remove" large sections of the beach and may make the rest of the beach unsuitable for bathing purposes due to a steepening of the beach profile and changes in nearshore currents. Such a loss of use of Durban's most valuable asset would have dire consequences for the tourist industry. A 1.0 m rise in the absence of protective measures would be disastrous for the local economy and the situation may be worsened by the possibility of changes in the storm climate and the effects of the underwater mound on wave focussing. An increase in the rate of beach nourishment will be essential to maintain the present beach status and an increase in demand for that borrow material may even be used as an early warning for increasing coastal erosion. Such an increase in rate of erosion may be useful as a proxy measurement of sea level rise which may bolster evidence from local tide gauge records.

The vulnerability of estuaries and inlets is again demonstrated in this case study. The effects of inundation and increased tidal effects will be limited as there is little development near the mouth and spit, but some ecological damage may be done to the mangrove communities. A prime example of poor town planning is illustrated by the threat from extreme water levels in the Umgeni. Much of the city is developed on the old river course and if the estuary breaks its banks, flood waters will naturally flow along their original route. A 0.5 m rise and a combination of sea and river floods would be sufficient to break the estuary's banks and flood Durban CBD down the railway line, NMR highway and golf course. Extensive engineering works will be necessary to counter this threat long before a 0.5 m rise is evident.

Any rise in groundwater will exacerbate existing engineering problems in the hotel district and the seafront but effective aquifer management techniques may be applied at a cost in order to lower the water-table in this area.

A 0.5 m rise in sea level will have very serious overall consequences for Durban. Although the impacts of a 0.2 m rise are probably just within the limits of natural variability of the system, the occurrence of any major storm activity will probably have considerable affect on Durban's beach and recreational characteristics. In the event of a 1 m rise, the survival of Durban's beachfront developments if left unprotected will be questionable but it is unlikely that suitable protective measures would not be carried out before such a rise.

4.4 The Impacts of Sea Level Rise on Walvis Bay

Walvis Bay is a small enclave of some 970 km^2 situated midway between the northern and southern borders of Namibia. The harbour is the only deep water port on this coastline and is of strategic importance to both South Africa and Namibia.

The whole coastline is essentially soft, sandy and erodible save for a few rocky outcrops. The bay is bounded to the west by a dynamic sandy spit, Pelican Point, and the town and harbour is located on the south eastern shore adjacent to the mouth of the ephemeral Kuiseb river which forms the Walvis Bay lagoon (Fig. 30). The area is a harsh desert environment with almost zero rainfall and as a result, the town has no storm water drainage (Hughes et al. 1991c). Consequently, detailed topographic plans for the town and harbour do not exist. Most of the town, harbour and adjacent coastline is very low lying with elevations of between 1 m and 3 m above Land Levelling Datum. The mean spring tidal range in the bay is 1.42 m and MHWS and HAT are at 0.71 and 1.02 m respectively. The dominant wind direction is from the southwest (FDC 1974) and this creates a clockwise flow of surface water within the bay.

Fig. 31 is a landsat image of the region and illustrates the exceedingly dynamic sedimentary environment of the study area. The Kuiseb forms the northern boundary of the Namib Desert which can be clearly seen as the longitudinal dunes to the south. Aeolian transport rates are in the region of 150 m^3/m/year northwards (CSIR 1989b), and periodic floods remove the encroaching dunes from the riverbed and redeposit the sediment in the area to the south of the spit.

The dominant wave direction measured from the clinometer seaward of Pelican Point (Fig. 30) is between 225° and 270° with effectively no waves from other directions. The design wave specification for an approximate 1 in 10 year deep water significant wave height in open water is approximately 5 m (Rossouw 1989) but the presence of Pelican Point effectively shelters the harbour area from any direct wave action. Some diffracted and refracted wave energy does enter the bay though much reduced and within the southern part of the bay there is a net southwards movement of sediment with deposition just to the north of the harbour (FDC 1974). A net northwards movement occurs in the northern part of the bay (FDC 1974). Pelican Point is migrating northwards at a rate of 17 m^3/year measured over the last 200 years and sections of it are prograding seaward at rates of between 5 m and 10 m/year (Hughes et al. 1991c). Rates of transport on Pelican Point are of the order of 2 x 10^6 m^3/year northwards and within the bay, 200,000 m^3 to 50,000 m^3/year southwards in the southern section (CSIR 1985) and 500,000 m^3/year northwards in the northern section (FDC 1974). Note that these rates are order of magnitude estimates and their consistency throughout the year are uncertain. Fig. 32 summarises the wave orthognal and sediment transport directions.

Walvis Bay is entirely dependent on a small coastal aquifer for its freshwater supplies. This aquifer may best be described as a lens of freshwater with very low hydraulic gradient (0.6 x 10^{-3}) fed by a narrow aquifer underlying the Kuiseb river (Hughes et al. 1991c). Fig. 33 shows the outline of the aquifer, its approximate area below 1 m elevation, the location of the main extraction wells and the position of the saline wedge. Should uncontrolled extraction take place the area for potential saline pollution below approximately MHWS (0.71 m) is clear. Although extraction from within this area is not yet taking place, there are plans for new extraction wells for this area in the near future (Hughes et al. 1991c).

Fig. 34 shows the inferred elevation of the top of the phreatic surface and surface topography. Note that salt water intrudes under the whole of the town. The saline water-table is generally within 0.7 m and 0.9 m of the surface (Hughes et al. 1991c).

This case study considers scenarios of 0.2 m, 0.5 m and 1.0 m rise in sea level.

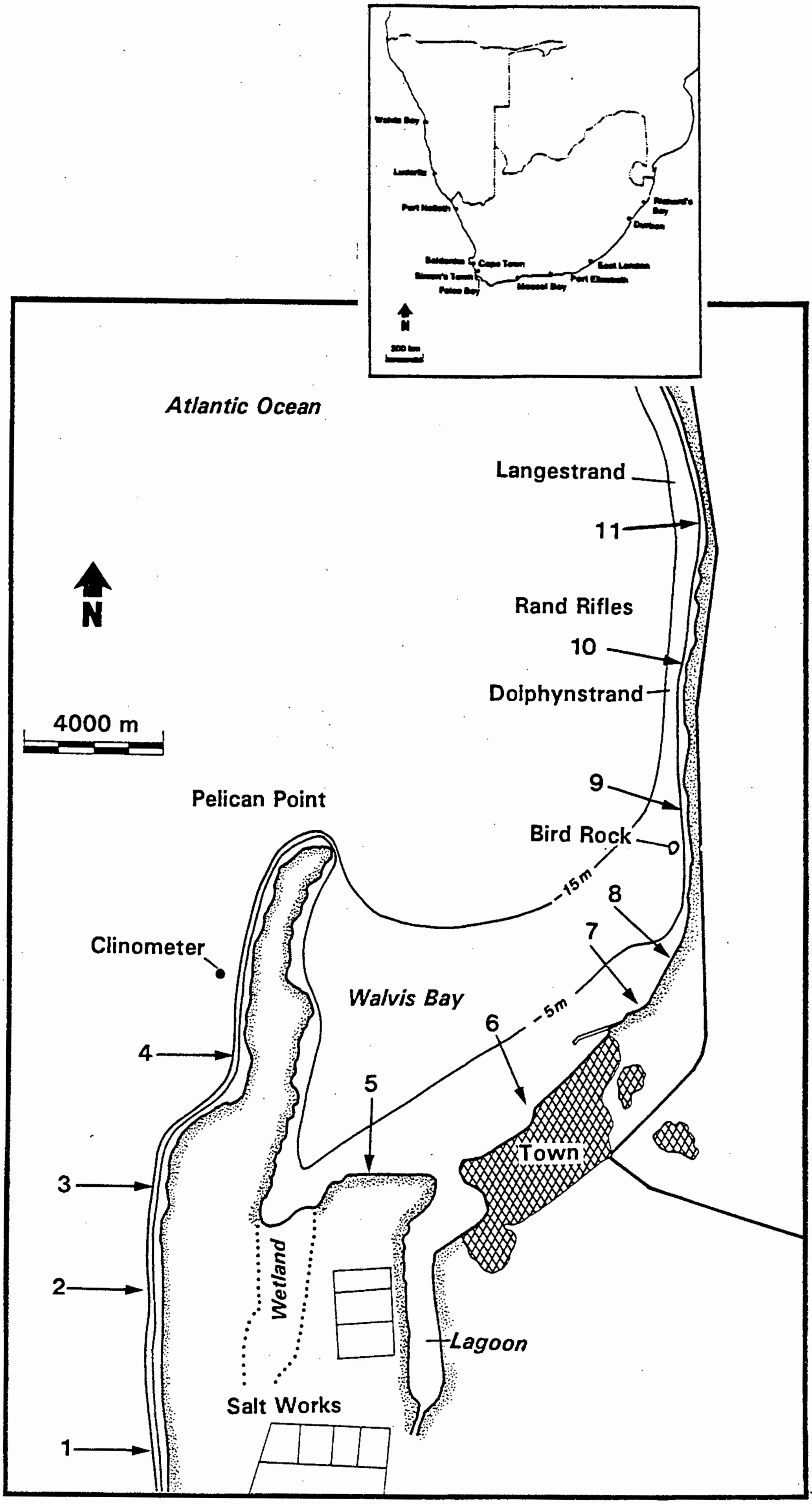


FIGURE 30. Location of Walvis Bay (after Hughes et al. 1991c).

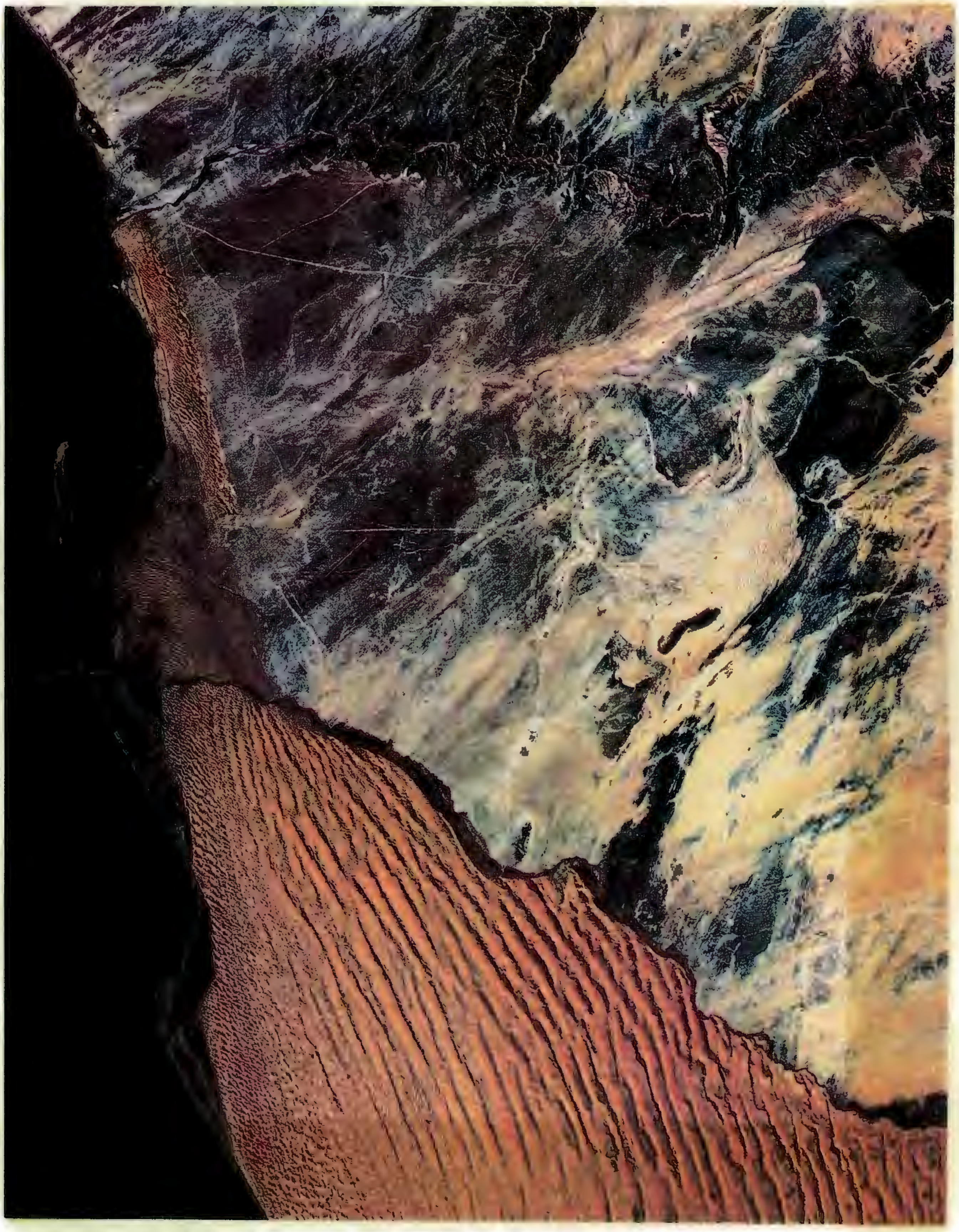


FIGURE 31. Landsat image of the Walvis Bay area, the Kuiseb river and the northern section of the Namib desert (after Sheffield 1981).

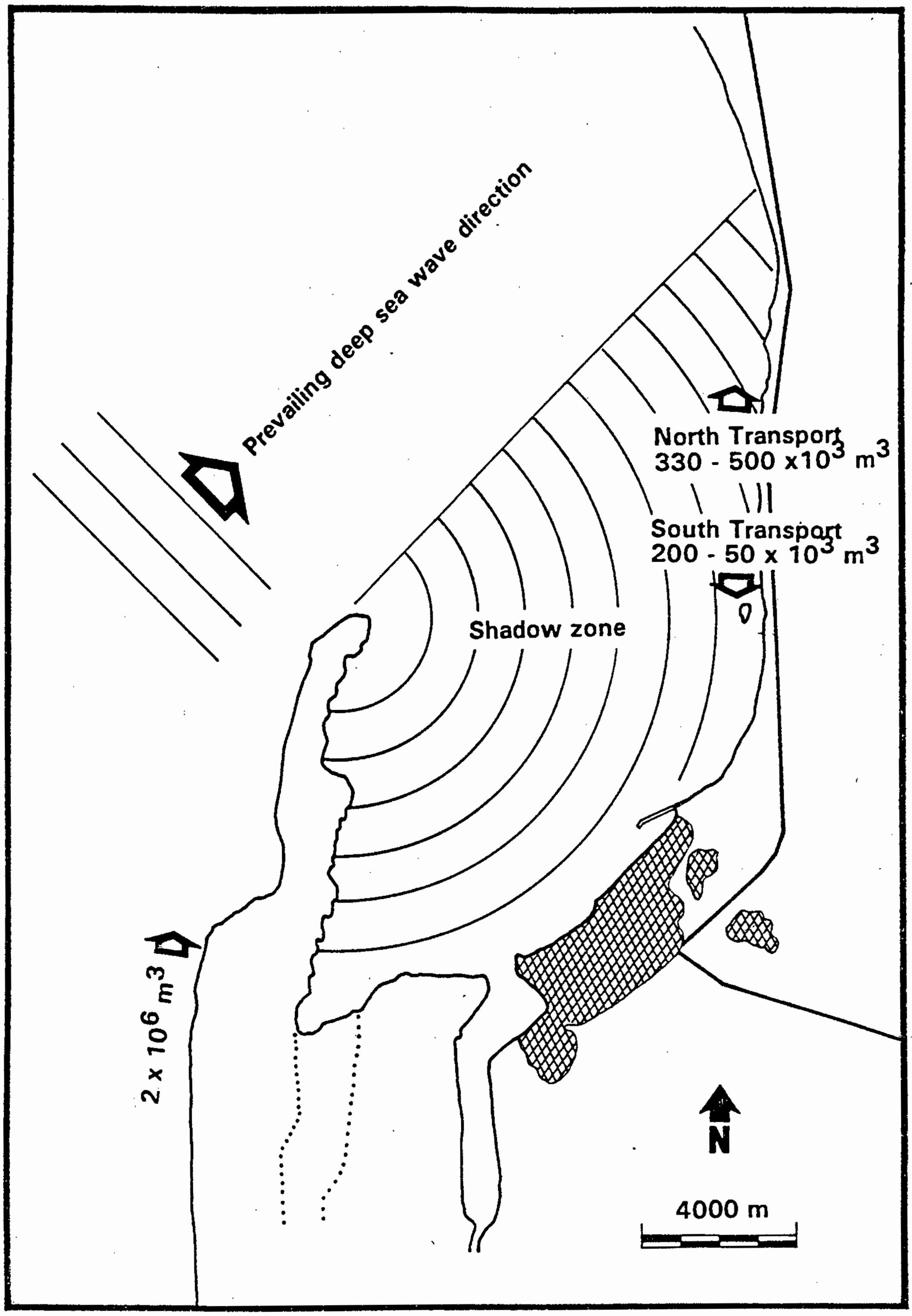


FIGURE 32. Summary of net sediment transport rates and wave orthognals (after Hughes et al. 1991c).

4.4:1 Site Parameters

Increased erosion is modelled by application of the Bruun Rule (1962) to the profiles shown in Fig. 30, using extensions to accommodate changes in rates of longshore transport (equation 5, C.3.1:1). Berm heights were conservatively estimated to be between 1 m and 5 m from the most recent orthophotos and personal communications. Average profiles were derived from the SA Navy Hydrographer's Chart SAN 1001.

The extent of inundation is modelled by assuming those areas of land adjacent to the coast with direct access to the sea below 0.9 m, 1.2 m and 1.7 m elevation, will be flooded at MHWS under the respective scenario.

Salt water intrusion into the aquifer was modelled using equation 12 (C3.1:3)

The elevation of the saline water-table under the town is assumed to increase at the same rate as the rising sea levels. The maximum level is taken as equal to MHWS.

The effects of extreme events are modelled by considering the return probabilities of actual water levels recorded on the Walvis Bay tide gauge and adding sea level rise to these levels. These levels contain a storm surge component but do not consider the effects of wave set up. This is realistic for Walvis Bay as Pelican Point affords excellent protection to the harbour from the prevailing wave direction. Hence set-up is likely to be very small.

4.4:2 Results

Application of the Bruun Rule (1962) to the 11 profiles located as shown in Fig. 30 provides the results shown in Table 9 for the three scenarios. Rates of longshore sediment transport are uncertain and have been bracketed in their use for Profiles 7, 10 and 11. Negative values imply deposition or progradation of the shore.

TABLE 9. Coastal recession in metres for Walvis Bay as indicated by application of the Bruun Rule

	EROSION			**dQ/dx (m^3/m)**
PROFILE	**0.2m Rise**	**0.5m Rise**	**1.0m Rise**	
1	4	10	21	0
2	4	11	22	0
3	4	10	21	0
4	18	45	90	0
5	95	236	473	0
6	86	219	432	0
7A	24	57	202	50,000/2,000
7B	-20	-55	-65	100,000/2,000
8	85	215	371	50,000/3,000
9	28	70	142	0
10A	117	300	400	330,000/5,000
10B	168	408	561	500,000/5,000
11A	136	350	467	330,000/5,000
11B	418	502	654	500,000/5,000

Negative values imply progradation

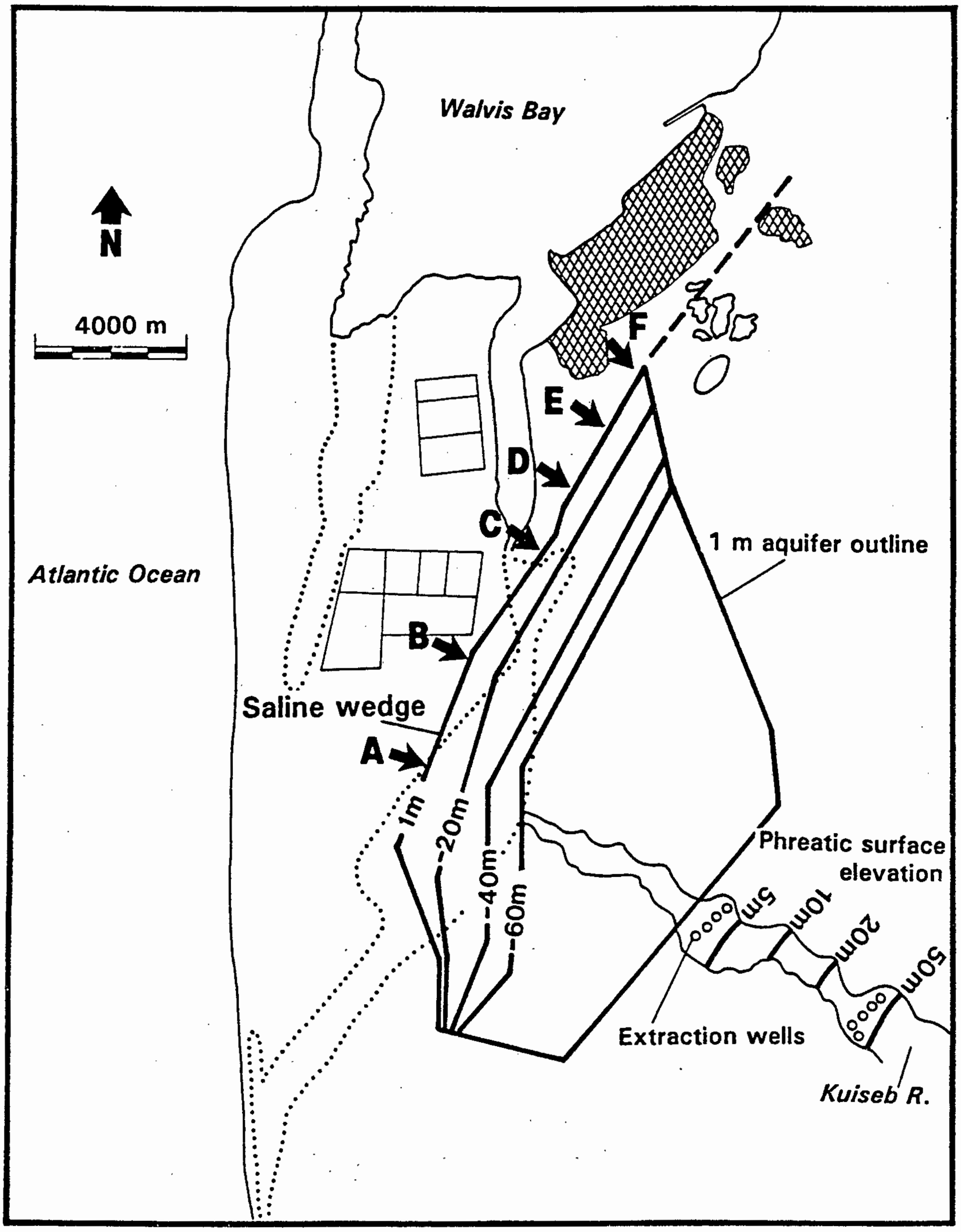


FIGURE 33. Outline of the Walvis Bay Aquifer, showing the position of the saline wedge and freshwater drawpoints and hydrological profiles A to F (after Hughes et al. 1991c).

Table 10 shows the anticipated saline wedge intrusions under present extraction rates for the three scenarios applied to the profiles A to F indicated in Fig. 33. The calculations assume a simplified topography and uniform hydraulic conductivity. The results show that the amount of increased intrusion is much less than the maximum possible if freshwater flow rates are reduced, and will have negligible impact. If freshwater extraction rates exceed approximately 4000 m^3/d in this aquifer the position of the saline interface will continue to migrate landward reducing the usable freshwater reserves (Hughes et al 1991c).

TABLE 10. Saline intrusion for sea level rise in Walvis Bay Aquifer

PROFILE	INCREASED SALINE INTRUSION (m)		
	0.2m Rise	**0.5m Rise**	**1.0m Rise**
A	95	238	476
B	55	139	278
C	15	37	75
D	15	37	75
E	333	348	373
F	105	262	450

Fig. 34 shows the elevation of the water-table surface and the topography. Any change in sea level will be accompanied by a similar change in the water-table. Virtually the whole town lies below 2 m elevation and a few locations are very low lying, around 1 m elevation and below. Any increase in water-table from its present position at about MHWS (0.71 m) will have serious consequences for the whole town. A 0.2 m rise will probably cause the Voelparadys vlei to expand slightly and areas below 0.9 m, such as near the hospital and schools, will flood. A 0.5 m rise would further enlarge the vlei, flood a greater proportion of the town and harbour and probably cause engineering and pollution problems in areas such as the cemetery and sewage works. A 1.0 m rise in water-table would be likely to flood the majority of the town below

1.7 m elevation. These water levels will be unaffected by freshwater extraction rates.

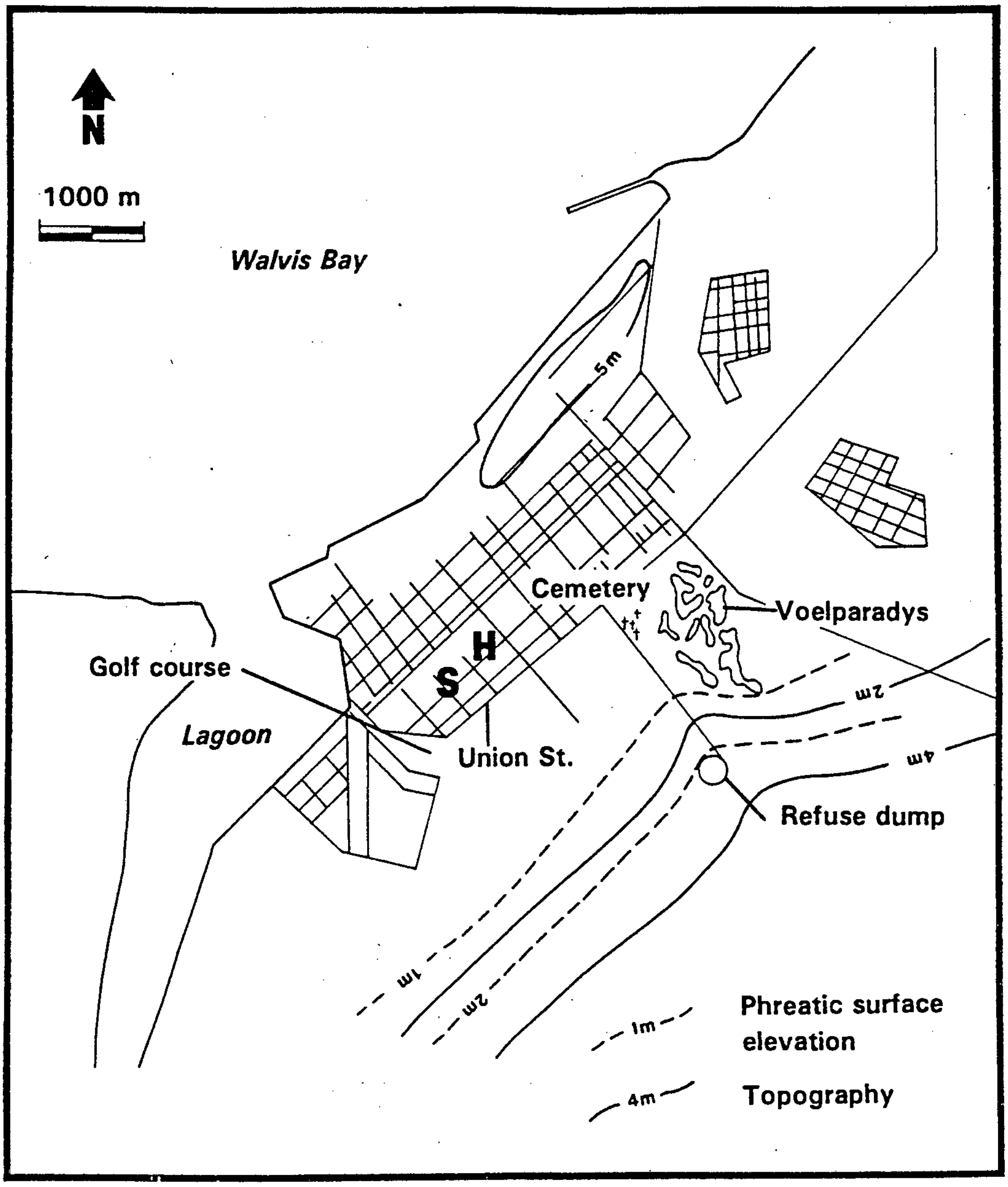


FIGURE 34. Approximate phreatic surface and topography elevations (after Hughes et al. 1991c).

Fig. 35 shows the extreme water level return period curve for the present sea level at Walvis Bay plus the curves for MSL plus 0.2 m and 0.5 m . The present level plot shows that Walvis Bay is very well sheltered from the effects of direct wave action and storm surge by Pelican Point and extreme levels are very rare; the water levels achieved during an annual event and a 1 in 100 year event fall within a very narrow range of 1.08 m to 1.24 m.

A rise in sea level of 0.2 m would therefore put the annual occurrence water level at 1.28 m - a level greater than the present level's 1 in 100 year event. During a storm any wave action or chop will tend to increase the practical level of the wetted area and it is possible to say conservatively that all land levels below the predicted water level will be flooded in the absence of preventative measures.

After a rise in sea level of 0.2 m all land below 1.36 m adjacent to the coast may be flooded with an expected frequency of once in every 10 years. This level is possibly greater than that achieved if a 1 in 1,000 year event were to happen now.

After a rise of 0.5 m a 1 in 10 year storm will flood all land below 1.66 m elevation and the future MHWS will be higher than is probably attainable now during any possible storm.

The effects of a 1 m rise are beyond the scope of this predictive method.

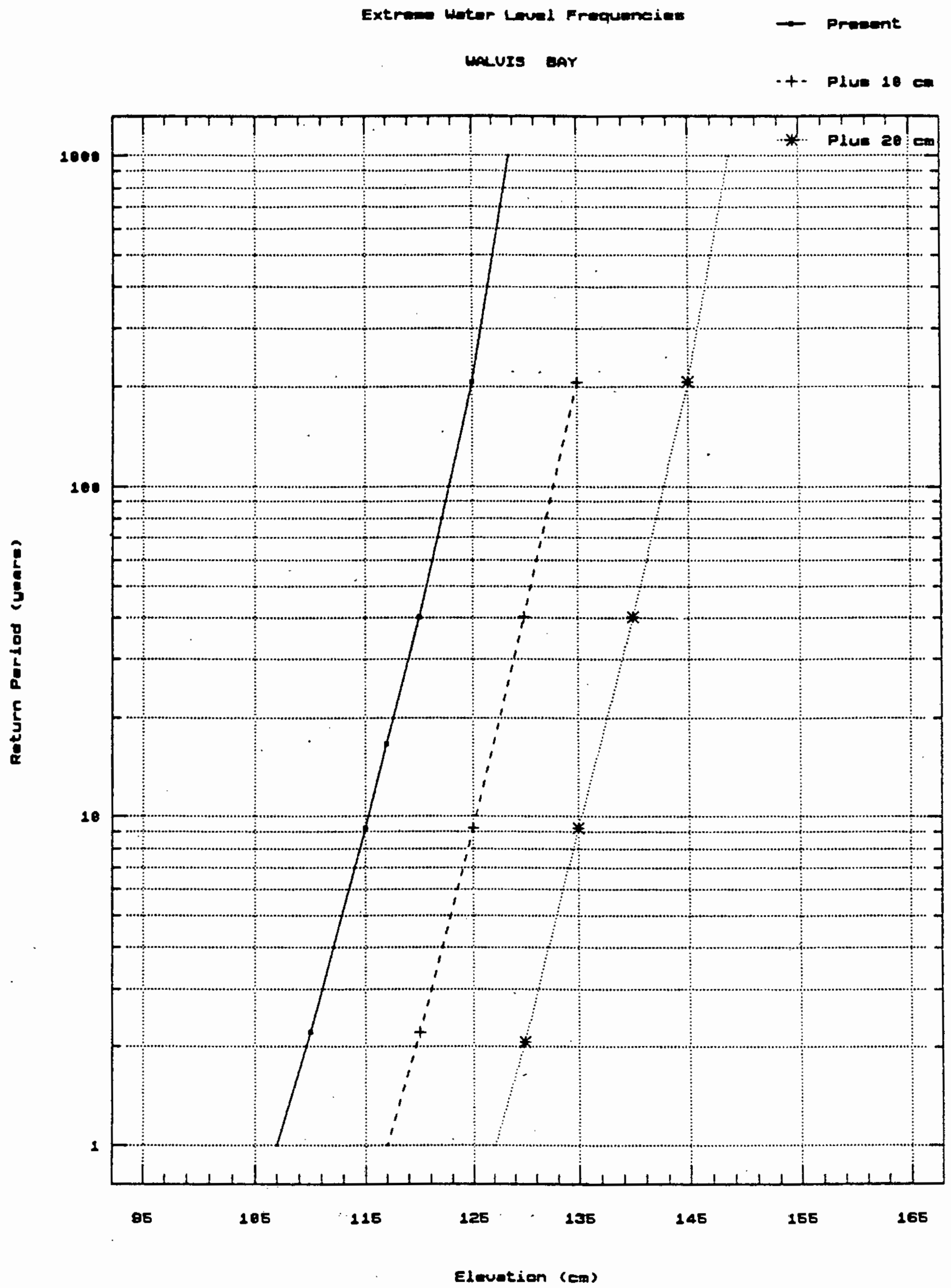


FIGURE 35. Extreme water level return frequencies for Walvis Bay with increments of 20 cm and 50 cm in sea level (after Searson *in prep.*).

4.4:3 Discussion

Prediction of rates of increased erosion in such a dynamic and poorly quantified sedimentary environment can at best be described as a hazardous occupation and at worst, a fruitless task. Detailed sediment budget studies would be necessary to improve on the predictions but even then future variables are too great to consider these predictions reliable. However, in this case the predictions are of little consequence. The open coastal margin is such a harsh and active environment that in the past, development has either been undesirable or impossible. The environment is unlikely to change to such an extent that coastal margin development will be desirable. Consequently any future shoreline changes within the anticipated range (Table 9) is likely to be of limited impact to the local infrastructure and may be easily managed or even ignored.

Equally difficult to predict in this mobile environment is the area of land likely to be flooded at high tide save to say all areas below 0.9 m, 1.2 m and 1.7 m may be inundated under the three scenarios. Land will probably continue to prograde from the southwest squeezing up against salt works and eventually squeezing the lagoon against the town which may have some ecological consequence. Production in the salt works will be affected as the base level for the pans is at approximately 1 m elevation. Much of the town is at 1 m elevation and unless protected, inundation could take place through the lagoon mouth, onto the golf course and Union Street.

Of greater consequence to Walvis Bay are the changes in groundwater levels which will probably match changes in sea level. As a result, those low lying areas vulnerable to inundation, will be vulnerable to waterlogging even if shore protection work is carried out. Lowering of the saline water-table under the town by extraction within artificial water compartments is likely to be prohibitively expensive. The exact delineation of those vulnerable areas in the town is not yet possible due to the absence of detailed topographic plans.

In terms of the vulnerability of the Kuiseb aquifer to saline pollution it is unlikely that rising sea levels and increased saline intrusion will create major pollution problems. Moreover, it is likely that freshwater extraction rates will have a far greater effect on the interface position than the anticipated change in sea level. In fact the demand and availability for freshwater may eventually determine the viability of the town in the future.

By far the most serious consequence for Walvis Bay is the risk due to increased storm water levels. As a result of the efficient sheltering by Pelican Point, the range of storm water levels, which do not include a wave set up component, is small. Development has therefore taken place using a narrow safety margin above "normal" water levels and the likelihood of an extraordinary event occurring is taken as "part of the risk". A change in sea level shifts the range of "acceptable" levels and the "norm" quickly moves into a category of intolerable risk to present development with only a small change in mean sea level. For such a low lying town the effects could be disastrous with a 0.2 m rise having a more devastating impact than a 1 in 100 year storm at present levels and a 0.5 m rise having greater effect than any storm currently possible.

Walvis Bay can be regarded to a certain extent as analogous to a very open tidal inlet. Some of the impacts of sea level rise on Walvis Bay therefore represent the type of impacts important to many inlets and estuaries and this case study should be borne in mind when considering all sheltered and low lying environments.

The majority of the town lies below 2 m elevation and when considering the combined impacts of a small rise in sea level and a moderate sized storm - the ability of the town to survive may be reduced long before the larger, modelled rise actually takes place. Detailed surveys of the town and environs do not exist - their completion is an essential first step towards managing the sea level rise impacts.

4.5 Case study review

In reviewing the case studies from four different types of environment it is clear that at each location different conditions and rules apply. However, although the relative magnitude of the impacts of sea level rise are site specific, these impacts are not unique to South Africa and have been documented elsewhere on numerous occasions, especially in areas of rapid relative sea level rise (e.g. Leatherman 1984, Titus 1990). Nevertheless, a number of generalizations and observations may be made which are of use in extending the impact assessments to other locations in South Africa.

The grouping of the impacts of sea level rise into four categories provides a good standard methodology with which to begin assessing the potential vulnerability of a site. By dealing with each impact in turn, the most hazardous may be quickly recognised and its logical conclusion, feedback/interaction with other impact groups and management potential may be efficiently followed up. But, when used in a more regional context, it appears to be too generalised and glosses over some important impacts and stresses others which are unimportant in the South African situation:

The category of increased coastal erosion is clearly important to all soft (unconsolidated) coastlines and the degree to which the impact is felt is a function of exposure to prevailing forces, bathymetry, topography and geology. Gently sloping profiles will be eroded faster than steep profiles and the presence of a high berm or backing dune tends to reduce the impacts. Likewise the presence of rocky outcrops, which may reduce wave action or prevent the equilibrium profile migration, will tend to reduce shoreline recession although the effect is difficult to quantify.
The effect of longshore sediment transport and transport gradients on the predictions of increased erosion may be modelled but only up to a certain degree. The confidence in transport rates must be good, even though the rates may be expected to change in the longer term coastal evolution and they must not be of extreme magnitude. Changes in rates of longshore drift (or demand for borrow material) may be used as an early warning system for rising sea levels.
Hard engineering solutions to the erosion problem, such as in places where the beach is topped by a seawall, create their own set of difficulties. In such places lowering of beach elevation, loss of beach width and change in

general beach and nearshore current configuration may occur. This in turn will have an effect or feedback on rates of longshore sediment transport and may detract from the beach's desirability.
Ribbon development or infrastructure built along the coast with insufficient freeboard or buffer zone between itself and the sea should be avoided wherever possible.

In terms of flooding and inundation it is generally only the inlets, river mouths, estuaries and coastal wetland vleis which will be affected, not the open coast. The internal tidal prism and stable channel dimensions may be modelled with a moderately high degree of confidence based on empirical studies and theoretical stabilities. However, there may be an increase in the tidal current velocities in the flooded area and this may be important, especially to structures crossing the areas or developments close to mobile banks and mouths. Any change to the dimensions of the channel can have an amplified effect on the extent of flooding. Modification to the channel and mouth dimensions by methods other than increased coastal erosion are not directly addressed by the four categories system (e.g. accelerated mouth migration or channel widening) and should be included in any regional assessment. As a result of an increased tidal prism freshwater systems may become more marine influenced with an associated change in ecology. In some instances this may represent an improvement for present conditions which are poorly flushed or highly polluted.

Salt water intrusion into inlets and estuaries is governed by slope of the inlet bed and rate of freshwater flow. Detailed examination of these parameters are necessary for accurate assessment and could form the basis of a study in its own right. Most inlets and estuaries in South Africa have sufficient slope to prevent extreme intrusion and save for some ecological changes (e.g. mangroves) the impacts are not likely to be too severe. There are, however, a few exceptions to this generalization which have large tidal exchanges (e.g. Breede River).
The effect of increased intrusion into coastal aquifers can be very localized and is difficult to generalise. Overall, the magnitude of increased intrusion is likely to be relatively small in comparison with aquifer dimension, and governed more by hydraulic gradients and freshwater extraction rates than by rising sea levels. In isolated coastal locations with boreholes and wellpoints close to the sea this increased intrusion may have serious

consequences, but in general the impacts may be managed. The use of the intrusion parameter on anything more than a site specific scale is limited.

Changes in water-table elevation has potential to cause serious engineering problems in developing and built up areas with high water-tables. In some cases the water-table may break surface if uncontrolled. If the water-table is non-marine, then it may be managed (at a cost) and the water-table lowered. If the raised water-table is saline (e.g. Walvis Bay) then it is likely to be prohibitively expensive, if at all feasible. Identification of high water-table areas and present positioning of the saline interface is therefore important.

The effect of reduced protection from extreme events is a serious problem for all sections of the coastal environment but especially so in those sheltered embayments, inlets and estuaries. Only a small increase in MSL is sufficient to change the risk of occurrence of an extreme water level, from an acceptable risk, to almost a certainty. In addition accompanying the high storm water level would be a significant amount of short term erosion which must be considered in factor of safety type calculations.

Chapter 5

REGIONAL IMPACTS

An assessment of global hazards from rising sea levels has been proposed by Gornitz and Kanciruk (1989) based on the division of hazards into two major categories:

1. Inundation and flooding, both permanent and episodic.
2. Erosion.

The assessment is an attempt to classify the coastal environment using a cumulative ranking of hazards based on physical conditions in the environment. It is intended to be applicable world wide and considers the following components: Relief; lithology; landform; vertical land movement; shoreline displacement; tidal range; and storm wave height.

Using these components a coastal vulnerability index (CVI) can be developed (Gornitz and Kanciruk 1989) which comprises "some combination of inundability variables (relief, subsidence) and erodibility variables (lithology, landform, wave height and tidal range)."

For this CVI, coastal relief based on global digital elevation at 5' latitude and longitude resolution provides a first order approximation of inundation. Lithology is interpreted directly from geological maps and a simplified classification is used which differentiates between resistant crystalline rocks, sedimentary rocks and unconsolidated sediments. Coastal landforms are interpreted from 1:250,000 topographic maps and classified into those formed by erosion and those formed primarily by deposition, both marine and non-marine. Relative sea level changes are obtained from tide gauge records longer than 20 years. Historical shorelines are digitized and averaged into 3' cells, with tidal range taken from Tide Tables and U.S. wave data supplied by the Wave Information Study carried out by the U.S. Army Corps of Engineers.

The seven components of the coastal hazards data base are manipulated by Geographical Information System (GIS) software and for each portion of the coast a risk rating or CVI is derived. Table 11 summarizes this global CVI.

TABLE 11. COASTAL VULNERABILITY INDEX (after Gornitz and Kanciruk, 1989).

RANK	VERY LOW	LOW	MODERATE	HIGH	VERY HIGH RISK
VARIABLE	1	2	3	4	5
Relief(m)	> 30.1	20.1 - 30.0	10.1 - 20.0	5.1 - 10.0	0 - 5.0
Rock type (relative resistance to erosion	Plutonic Volcanic (lava) High-medium grade metamorphics	Low-grade metamor. Sandstone & conglomerate (well cemented)	Most sedimentary rocks	Coarse and/or poorly-sorted unconsolidated sediments ash	Fine unconsolidated sediment volcanic
Landform	Rocky, cliffed Coasts Fiords Fiards	Medium cliffs Indented coasts Mangrove	Low cliffs Glacial drift Salt marsh Coral Reefs Alluvial plains	Beaches (pebbles) Estuary Lagoon	Barrier beaches (sand) Mudflats Deltas
Vertical movement (Relative Sea Level change)(m/yr)	≤ -1.1 Land Rising	-1.0 - 0.99	1.0 - 2.0 within range of eustatic rise	2.1 - 5.0	≥ 5.1 Land sinking
Shoreline displacement(m/yr)	≥ 2.1 Accretion	1.0 - 2.0	-1.0 - +1.0 Stable	-1.1 - -2.0	≤ -2.0 Erosion
Tidal Range, m (mean)	≤ 0.99 Microtidal	1.0 - 1.9	2.0 - 4.0 Mesotidal	4.1 - 6.0	≥ 6.1 Macrotidal
Wave height, m (maximum)	0 - 2.9	3.0 - 4.9	5.0 - 5.9	6.0 - 7.9	≥ 7.0

On a large scale this CVI is useful in identifying those vulnerable regions or countries, but its resolution is too coarse for successful application in South Africa where population pressures tend to be localised in habitats or niches smaller than 5'. It identifies problematical areas in terms of physical impacts/processes but does nothing to convey a sense of damage or loss to the inhabitants of those high risk areas. In addition, its components do not extend across the full range of conditions and environments found in South Africa, for example:-

> When considering the range of variability in Table 11 found around the South African coast and the experience gained from case studies, it is clear that areas of unconsolidated sediment, beaches, estuaries, lagoons and wetlands rank as high risk under this CVI. These environments account for more than 80% of the entire South African coastline
>
> In respect of the storm wave height variable storm wave heights around South Africa may be taken as moderate to very high with the southern,

southwestern and southeastern Cape coasts tending to experience the largest waves, and wave height diminishing slightly up the west and east coasts.

In respect of the relief variable, those low lying estuaries and wetland environments often found backing coastal dunes already shown to be vulnerable by the case studies, will all rank as moderate to high risk. However the 5' resolution is generally too coarse to pick out these environments and narrow coastal plains which are often highly developed.

South African rates of relative sea level rise (Hughes et al. 1991a) are within the range of eustatic estimates and the overall shoreline displacement appears more or less stable in most places indicating a moderate risk ranking. However, historical shoreline displacements are poorly documented and such a parameter is not ideally suitable for use in a South African CVI.

The lack of detailed measurements of variables around the South African coast (especially those such as shoreline displacement and local vertical land movements) preclude useful GIS manipulation. In addition, the observation that certain parameters in this CVI are not definitive in the South African case, limits this CVI's usefulness. However, it may be used in a broad sense in South Africa as an initial test of vulnerability to recognize those areas most likely to be vulnerable, e.g. the northern False Bay coastline as opposed to the Tsitsikama Forest Reserve coastline. Once the areas of interest are located a more detailed CVI may be developed which takes greater account of localized impacts. A CVI on this scale becomes a Coastal Management Tool (Hughes and Brundrit 1991a) and is applied here to two regions.*

5.1 The Development of a small scale Coastal Vulnerability Index with particular reference to South Africa.

Infrastructure vulnerable to or damaged by rising sea levels may be rated according to a quasi-"economic value" which may be calculated from a number of terms such as replacement value, loss of earnings or "desirability". For example, the effects of increased erosion on the embankment of a national highway may be considered more serious than erosion of vacant and unusable land adjacent to the shore. In order to develop a vulnerability index which will reflect the economic impacts of sea

* On completion of this thesis, a third method of vulnerability assessment was brought to the authors attention; the IPCC's (1991) Seven Steps to the Assessment of the Vulnerability of Coastal Areas to Sea Level Rise. This provides a common multi-disciplinary methodology for vulnerability assessment, is very detailed but unfortunately requires skills and data collection and assimilation beyond the capacity of a single operator. It is therefore not included in this chapter but is discussed in Chapter 6.

level rise at a given location, the risk analysis procedure must examine the risk to a range of infrastructure from a range of hazards.

A suitable classification for infrastructure in the South African coastal environment can be taken as:

- Private housing, holiday or residential
- Commercial property, e.g. shops, restaurants, hotels, industrial premises
- Developing and underdeveloped land - e.g. plots
- Major roads and sole access roads to that location
- Minor or secondary roads
- Railways
- Agricultural land
- Road bridges
- Rail bridges

Using experience gained from the detailed case studies reviewed at the end of Chapter 4, the hazard variables may be categorized into those of:

- Increased coastal erosion
- Increased inundation
- Effects of elevated groundwater-tables
- Vulnerability to extreme sea storms and river floods
- Risk due to increased tidal influence (e.g. within inlets and around inlet mouths)

Note that an additional category of increased tidal influence has been added to help identify inlets potentially vulnerable to mouth modifications and the category of saline intrusion has been dropped because of insufficient knowledge of South Africa's coastal aquifers.

From field observations at a location the likely impacts of sea level rise may be assessed and risk to particular classes of infrastructure established. This risk may be rated as high risk or low risk with the rating based on the expected geomorphological behaviour to changing water levels. Instead of carrying out detailed individual case studies, the results of the previous case studies (Chapter 4) are used as guidelines for the likely changes to most environments and a rapid vulnerability assessment can be made. The detailed methods employed in determining the geomorphological changes are described in Chapter 3 and the risk rating may be described as follows;

> Infrastructure and development at high risk to coastal erosion falls within the range of erosion predicted by a simplified application of the Bruun Rule (1962). Areas of low risk fall immediately adjacent to this range. Risk to flooding is governed by topography and proximity to the water level. Water-table elevations are estimated from sightings of seepage and proxies such as the occurrence of typical wetland vegetation. Vulnerability to increased tidal influence is based on local geology and geomorphology with such features as the tips of sandy spits and the outside of river bends ranking highest. Risk to storm flood damage is assessed in a similar manner to flood risk only expected storm water flood levels are used. Storm erosion is also considered in some instances and is based on a local approximation of potential damage and historical information.

In certain instances the resolution of the classification may be exceeded with infrastructure being at very high risk or very low risk. The extreme risks are simply grouped into high or low categories. The risks are then given a relative value or rating. Each high risk assessment is assigned a value of 2, each low risk assessment a value of 1 and no risk a value of 0. The assignment of risk may appear to be somewhat subjective but the use of detailed formula and stipulated boundary conditions would make the CVI too complex and unwieldy without necessarily improving the accuracy. The objective is to provide a relative assessment of risk rather than develop another global risk ranking and the experience gained from the case studies and use by a single operator reduces this subjectivity. Its small scale may make it useful in applications in other locations. The qualitative nature of this small scale CVI assigns it a "first model" status in the absence of suitable quantifiable data. It provides a follow up to the Gornitz and Kanciruk (1989) CVI which is used first to highlight areas of interest and then, by means of comparison, it identifies those most vulnerable types of environments found around the South African coast.

Having assessed the vulnerability of a number of locations in a region and assigned values to infrastructure and hazard, a comparison can then be made. The vulnerability index may be conceptualized as a three dimensional risk matrix R_{ijk} with components i, j and k denoting categories of location, infrastructure and hazard respectively. The total risk value for each location (A_i) is equal to the sum of all the hazard values assigned to all that location's infrastructure groups, i.e. $\Sigma_{jk} R_{ijk}$. The rating of each target infrastructure (B_j) in the study area (e.g. total risk to say private housing) is equal to the sum of all hazard values, at all locations, for that infrastructure group, i.e. $\Sigma_{ik} R_{ijk}$. The rating of each hazard C_k in the study area (e.g. risk from say storm damage) is equal to the sum of risk to all infrastructure groups, at all locations, to that hazard, i.e. $\Sigma_{ij} R_{ijk}$. After summing for each component and dividing by the number of vulnerable locations in that region to give a "unit vulnerability", the risks may be scaled by their minimum (non-zero) risk level in order to give a relative vulnerability to sea level rise for that study area. Thus the crude allocation of risk levels reflects the level of economic impact of sea level rise. Costing of the impacts is a function of the infrastructure category and location and may only be determined accurately on completion of detailed case studies. However, relative monetary impacts may be emphasized by using such indices as rateable value where such surveys are up to date.

Within a study area there may be a number of locations which are zero risk rated. The percentage of zero-rating in an area is also a useful measure of a region's overall vulnerability. However, great care must be taken with the choice of regional boundaries to ensure that major geomorphological boundaries are not transgressed. When comparing <u>locational</u> vulnerability between several <u>regions</u>, the results must be scaled by their overall minimum (non-zero) unit values in order to achieve relative vulnerability.

5.2 Application of the small scale CVI to the Southern Cape Coast

Application of the Gornitz and Kanciruk (1989) CVI ranks the relief and geology of the southern Cape coast as moderate to low risk, and the landform and wave height as high risk. The remaining variables are not useful in determining localized vulnerability although the ones used indicate the potential vulnerability of this area and qualify it for further investigation. A more detailed study was carried out on a 300 km stretch of coast between Witsands in the west and Nature's Valley in the east (Fig. 36).

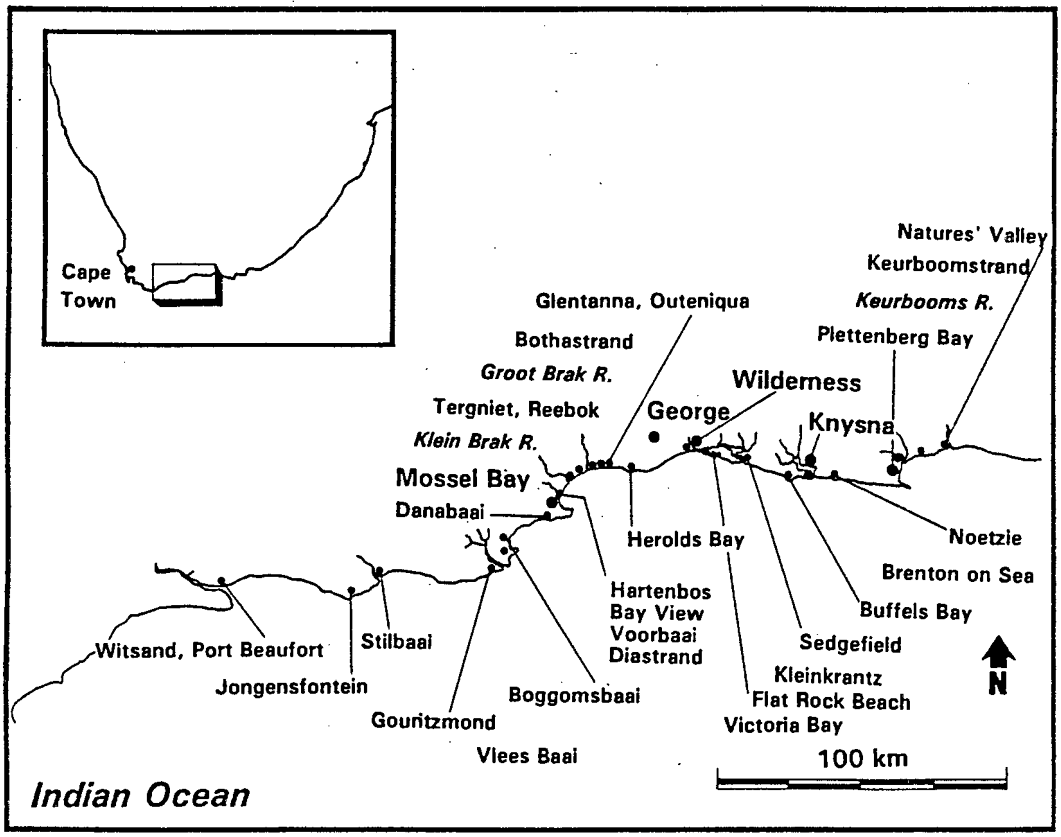


FIGURE 36. Location map of southern Cape coast area to which the South African Coastal Vulnerability Index was applied (after Hughes and Brundrit 1991a).

The dominant lithologies of the south Cape region are the Table Mountain quartzites with smaller areas of the Cape Granite suite and Uitenhage conglomerates between Mossel Bay and Plettenberg Bay. Bredasdorp sandstones and limestones predominate. Almost the entire coastline is bounded by a series of aeolian and marine sands and calcretes with the salient points tending to be outcrops of Table Mountain Series quartzites or granites. The gross geomorphology is a series of "half heart" bays of various scales up to 80 km across with long axes pointing eastwards. These bays are cut by a number of large rivers such as the Gouritz, Klein Brak, Groot Brak and Keurboom. Extensive wetlands exist along the Klein and Groot Brak rivers and in the Wilderness, Sedgefield, Knysna and Plettenberg Bay areas.

The south Cape coast contains several major coastal roads, railways and bridges and its residential and vacational housing in many instances are located in areas of outstanding natural beauty. Tourism forms a major part of the region's revenue with light industrial development centered around Mossel Bay and Knysna. Increasing population pressure in the area will generate larger industrial and commercial requirements which will most likely develop from existing infrastructure. Determination of vulnerability of this existing infrastructure is therefore prerequisite to assessing the impacts of rising sea levels in this area.

Thirty one locations (Fig. 36) between Nature's Valley and Witsands (Cape Infanta) were evaluated as described above for a one metre rise in sea level. Field observations were carried out over four days in May 1990, midway between spring and neap tides. The locations were determined by the presence of some development and the boundaries usually coincided with municipal district boundaries or district topographic features. Inaccessible sections of the coast with no development or infrastructure, were not considered for the analysis.

5.2:1 Results

Appendix 1 contains the risk values assigned to each location's infrastructure types (where present), for each of the five hazard categories (increased erosion, flooding and inundation, elevated groundwater-tables, extreme events and greater tidal influence). Fig. 37 shows the total relative vulnerability of each location to sea level rise, i.e the risk to all the infrastructure in each location from all sea level rise hazards. Five of the thirty-one locations namely Noetzie, Brenton-on-Sea, Voorbaai, Danabaai and Victoria Bay receive a zero rating in respect of all infrastructure to all hazards and consequently are omitted. The south Cape coast therefore has a 16% zero-risk rating. The remaining locations are ranked from a minimum value of 1 at Kleinkrantz up to a maximum at Groot Brak river.

The relative hazards rating determines the processes associated with sea level rise likely to be the most detrimental overall to infrastructure and development at locations along the southern Cape Coast. The summed risk values for each hazard are divided by the number of vulnerable locations in the area (26) and scaled by their minimum value. The rating is shown in Fig. 38. The rating shows risk due to extreme storm events to be the most important hazard along this coast and increased erosion to be the least.

The infrastructure rating (Fig. 39), shows the relative rating of each target group of infrastructure along this section of coast. Like the hazard rating (Fig. 38), the summed risk values for each infrastructure category are divided by the number of vulnerable locations (26) and scaled by their minimum value. This process gives an indication of where the economic impacts will be felt, suggesting that along this coastline, private housing will be affected the most and railways the least.

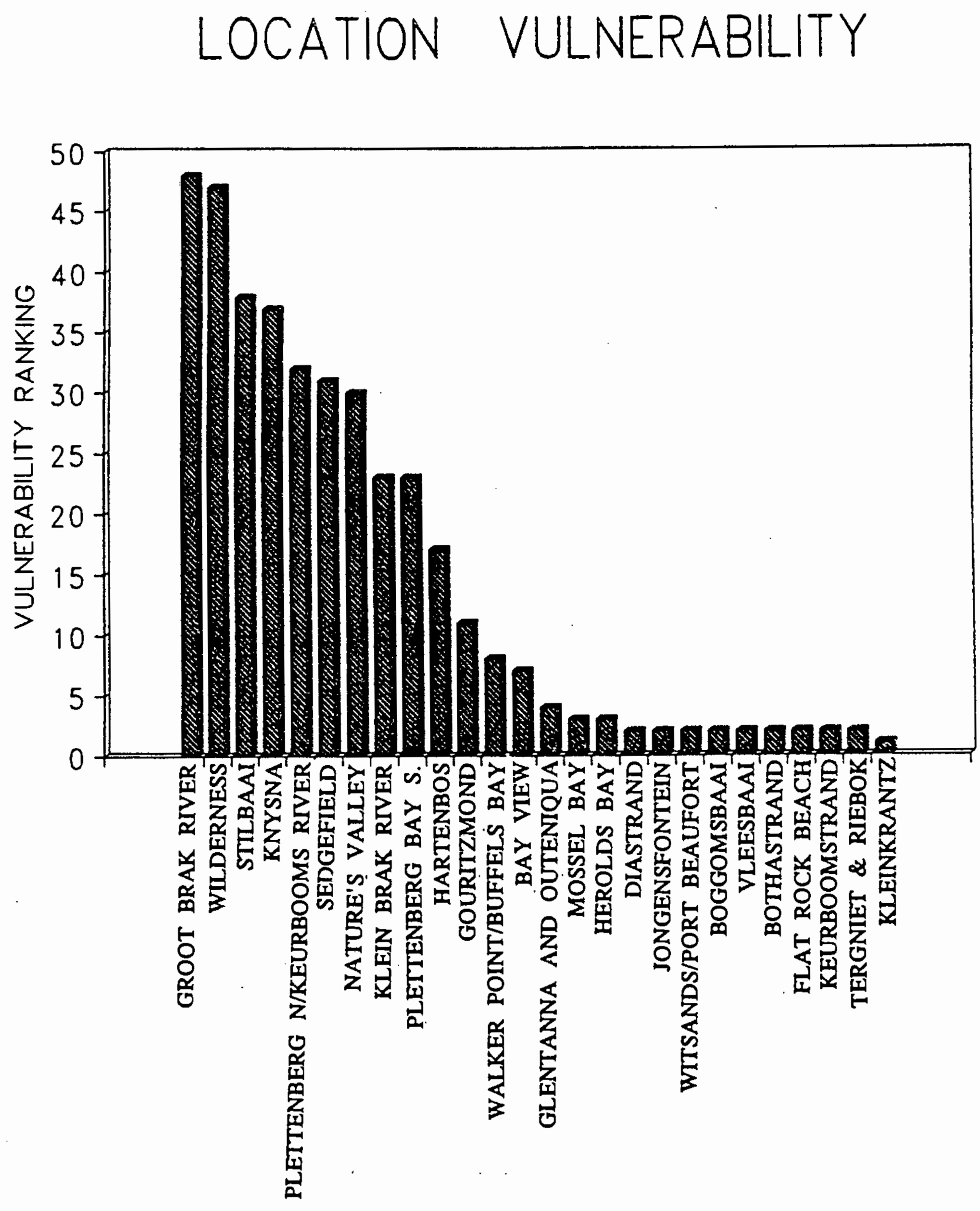


FIGURE 37. Relative location vulnerability along the southern Cape coast (after Hughes and Brundrit 1991a).

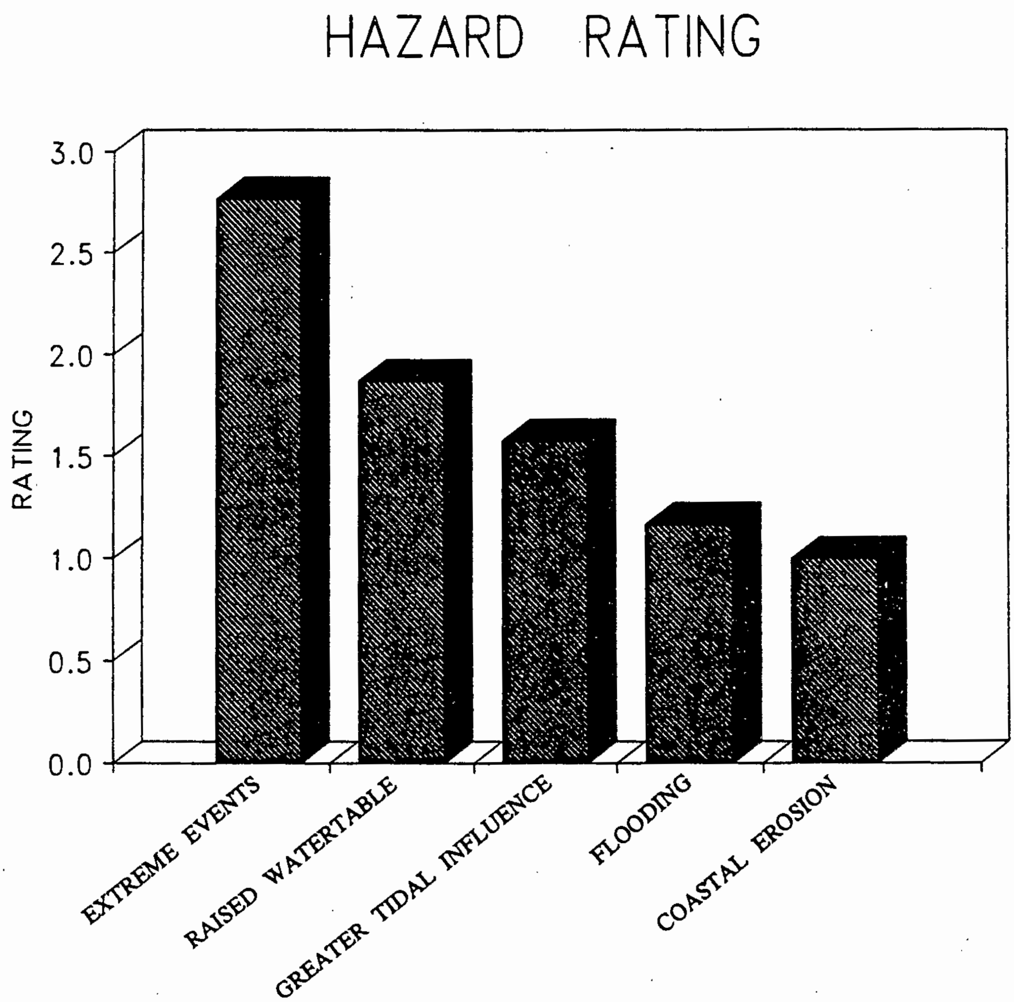


FIGURE 38. Relative hazard rating for the southern Cape coast demonstrating those processes associated with sea level rise most likely to be detrimental to infrastructure and development (after Hughes and Brundrit 1991a).

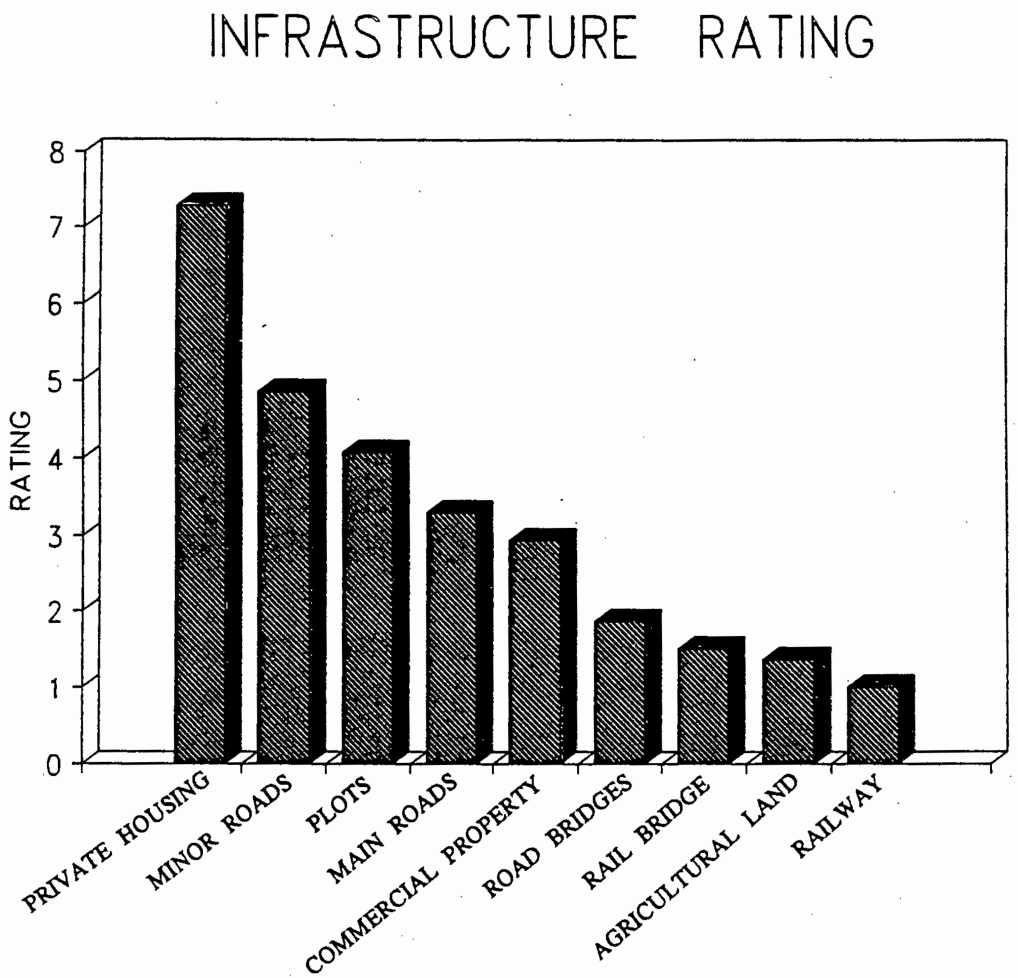


FIGURE 39. Relative infrastructure rating demonstrating which infrastructure and development categories are at greatest risk along the southern Cape coast (after Hughes and Brundrit 1991a).

5.2:2 Discussion

Within this study area, the areas of Groot Brak river and Wilderness would appear to be 10 times more vulnerable than places such as Mossel Bay and 50 times more so than Kleinkrantz as measured by this CVI. The location ranking shows an upward trend in vulnerability from fully exposed coastlines to pocket bays, open beaches, open estuaries through to semi-closed estuaries and wetlands. In reality this is a result of the sampling procedure which only looks at developed coastline and is simply a reflection of those places most suitable or comfortable for habitation with those "tranquil retreats" ranking highest. This reflection is, however, valid for the risk analysis as even future development will tend towards the more comfortable environments avoiding harsh and inhospitable sites.

Ideally, a unit Rand value for land at risk in those locations would be the best way of identifying which areas will suffer the severest economic impact and clarify any high value versus low vulnerability disparity. Unfortunately this type of information is not easily available and a proxy must be used. Such an alternative would be rateable value but unfortunately this too cannot be used with any degree of confidence as the surveys date back to 1972 and do not therefore reflect the true value of the area. Saleable value would give a better indication but would involve detailed investigation beyond the scope of this study.

The hazard rating (Fig. 38) shows that along this coast, increased coastal erosion has the lowest risk to infrastructure. This is hardly surprising as those high risk low lying developments close to the water's edge tend to be located inside sheltered embayments and estuaries in areas not exposed to direct wave action. Such areas would, however, be influenced by greater tidal current action and this is reflected in the hazard ranking. If these low lying high risk areas were exposed to direct wave action (- as in the west side of Milnerton after the channel breakthrough in the Diep river case study in Chapter 4 above -), then it is likely that the order of hazard ranking would change dramatically with increased erosion becoming one of the more important risks. At the moment, however, the most serious risk is that from extreme events, nearly three times the risk due to increased erosion. Elevated groundwater-tables also appear to be quite important but note that the relative rating for the hazards all fall within a narrow range.

With rising sea levels, less extreme and therefore more frequently occurring storms and floods will be capable of overtopping existing shore protection structures. Such an increased vulnerability is extremely well demonstrated in the Walvis Bay case study above. Construction of shore protection installations is generally extremely expensive, difficult to manage and, in most cases, aesthetically unappealing when located in areas of outstanding natural beauty. Wherever possible, storm protection defences should blend in with the natural surroundings. Undeveloped buffer zones, with or without artificial/natural dunes, bounding the shore/land interface can act as low maintenance, low budget shore protection installations and should be encouraged wherever possible. These topics are more fully discussed in Chapter 6.

Management of groundwater-tables is also expensive and difficult to achieve. Much of the development surrounding estuaries, lagoons and wetlands has taken place where the existing water-table is close to the surface. The slightest rise in sea level will lead to comparable rise in water-table, causing engineering problems. As discussed in the case studies this can be lowered (if freshwater) although usually at considerable cost.

The infrastructure rating reflects the economic platform. Private housing is seven times more vulnerable than railways and almost twice as vulnerable as commercial property. Developments are geared towards the tourist industry with the majority of the private housing being second or holiday homes and the minor roads being those routes, scenic or otherwise, which serve those dwellings.

In summary for the southern Cape coast between Nature's Valley and Witsand, private housing and secondary through routes (scenic?) surrounding river mouths, estuaries, lagoons will be the first victims of sea level rise. The greatest risks will be from extreme storm and flood events and groundwater flooding. The initial impacts are likely to be felt by the local resident/ratepayer/private individual and insurance company and will not therefore have a serious national impact. The effects of greater tidal influence and associated estuary mouth migration may have some slight national impact when those mouths are crossed by main or national highway bridges such as at Wilderness and Groot Brak river.

After the first impacts have been felt and attributed directly to rising sea levels, it is probable that insurance companies will re-evaluate their policies and decline to re-insure developments at risk for the same rate as before. In this area then, the financial impact will be pushed even further into the private individuals' lap - individuals who are generally less able to absorb the losses than large corporate or government bodies. However, those individuals will undoubtedly attempt to seek protective measures or alternative compensation for the impacts. Chapter 6 deals with responsibility and management philosophy in more detail.

5.3 Application of the small scale CVI to the Natal South Coast

Under the conditions laid out above for the Gornitz and Kanciruk (1989) CVI the relief of the Natal south coast ranks as moderate to low, the geology and landform as high and the wave height as moderate to high. The remaining variables are not useful in determining a localized vulnerability, but these are sufficient to rank the Natal south coast as being of moderate to high vulnerability to sea level rise and worthy of further investigation.

The Natal south coast is a very straight section of coastline which faces almost due south east. Most of the shore and nearshore is sandy and the beaches are generally backed by large, well vegetated dunes. Rocky outcrops do occur on many beaches either as small promontories and headlands or wavecut platforms and beach rock near the low water mark. The underlying lithology is predominantly Karoo shales, sandstones and grits and the coast is sub-parallel to the axis of the Natal Monocline. The coastal plain is generally quite narrow (where present), hence the moderate to low ranking of relief under the Gornitz and Kanciruk CVI (1989), and is cut by numerous straight and steep-sided drowned valleys indicative of rapid tilting and marine transgression in the geological past. Tide gauge records for the east coast of South Africa are generally short and of poor quality and it is uncertain whether some localized tectonics are still occurring. Tectonic movement can not be recognized from these tide gauge records but it is generally felt that this section of the coast is relatively stable. Beaches are generally medium to very coarse grained, they tend to be steep with a narrow flat berm on top. Backing dunes are usually very well vegetated and along much of the coast, especially in very highly developed areas, there are dune protection programs. The dominant deepwater wave direction is from the south and south-south-east but inshore the waves are refracted to be nearly shore-parallel.

Development is generally well set back from the beach either high up, on or behind dunes. The Natal south coast is a major tourist venue with many hotels, tourist centres and holiday and retirement homes dotted along its length. In a sense, ribbon development has taken place along the coast although the narrowness of the coastal plain and the high dunes have precluded much development close to the water level. In general where access to a beach is required in the built up areas, it is provided on a nodal basis with distinct access points, complete with municipal car parks, swimming pools and beach cafes, - i.e. it is well controlled. However, when the coastal road and railway lines were built, the easiest (flattest) route was sought and the road and rail tend to follow the shore very closely, cutting across river and lagoon mouths where necessary. In places, the embankments supporting the railway and minor service roads are actively being eroded where they cross the tops of beaches in such places as Port Shepstone and Brighton Beach.

The small scale CVI (Hughes and Brundrit 1991a) was applied as described above and seventy nine locations were examined from Sloan Road on Durban Bluff to Port Edward (Fig. 40) during field observations between 19 and 25 November 1990. Their vulnerability to a one metre rise was assessed. Observations were carried out just after a spring high tide, approaching neaps.

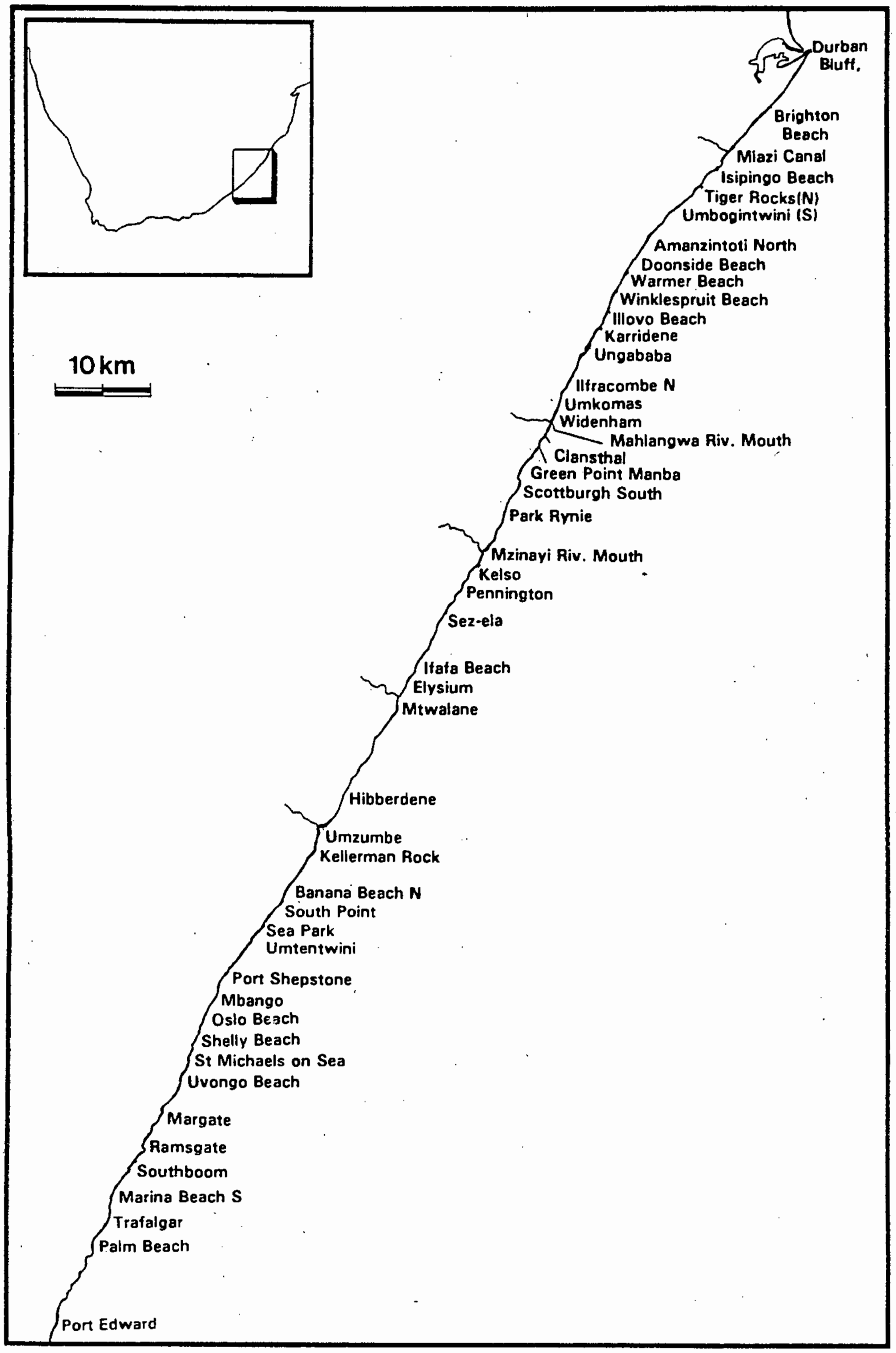


FIGURE 40. Location map of the area of Natal south coast to which the South African Coastal Vulnerability Index was applied.

5.3:1 Results

Appendix 2 contains the values assigned to each infrastructure category from each hazard category for each of the locations along the Natal south coast. As in the south Cape coast application (section 5.2), the summed hazard and infrastructure values are divided by the number of vulnerable sites (55) to provide a unit rating for this study area.

Fig. 41 shows the relative location risk for the study area but excludes all those locations with a zero rating (Table 12). Twenty-four of the seventy-nine sites or 30 % were assessed zero rated or safe from a 1 m rise. Locations such as Umzumbe, Clansthal and Port Shepstone appear to be between 10 and 13 times more vulnerable than Port Edward and Southport.

Fig. 42 shows the relative hazard rating for the Natal south coast and shows that in this area the risk due to extreme storm events is nearly twice that due to increased erosion and three times that due to increased tidal influence. By comparison, the risk due to raised water-tables and inundation appear negligible. The wide range of the hazard rating suggests those erosional processes are considerably more important in this study area than those inundational or intrusional processes.

Fig. 43 shows the risk to target infrastructure and suggest that commercial properties and municipal "services" are at greatest risk along with minor access roads and car parks. (Municiple "services" in this context is used to describe beach cafes, pools, toilets and other beach facilities.) Railways and rail bridges are more than twice as vulnerable than private housing.

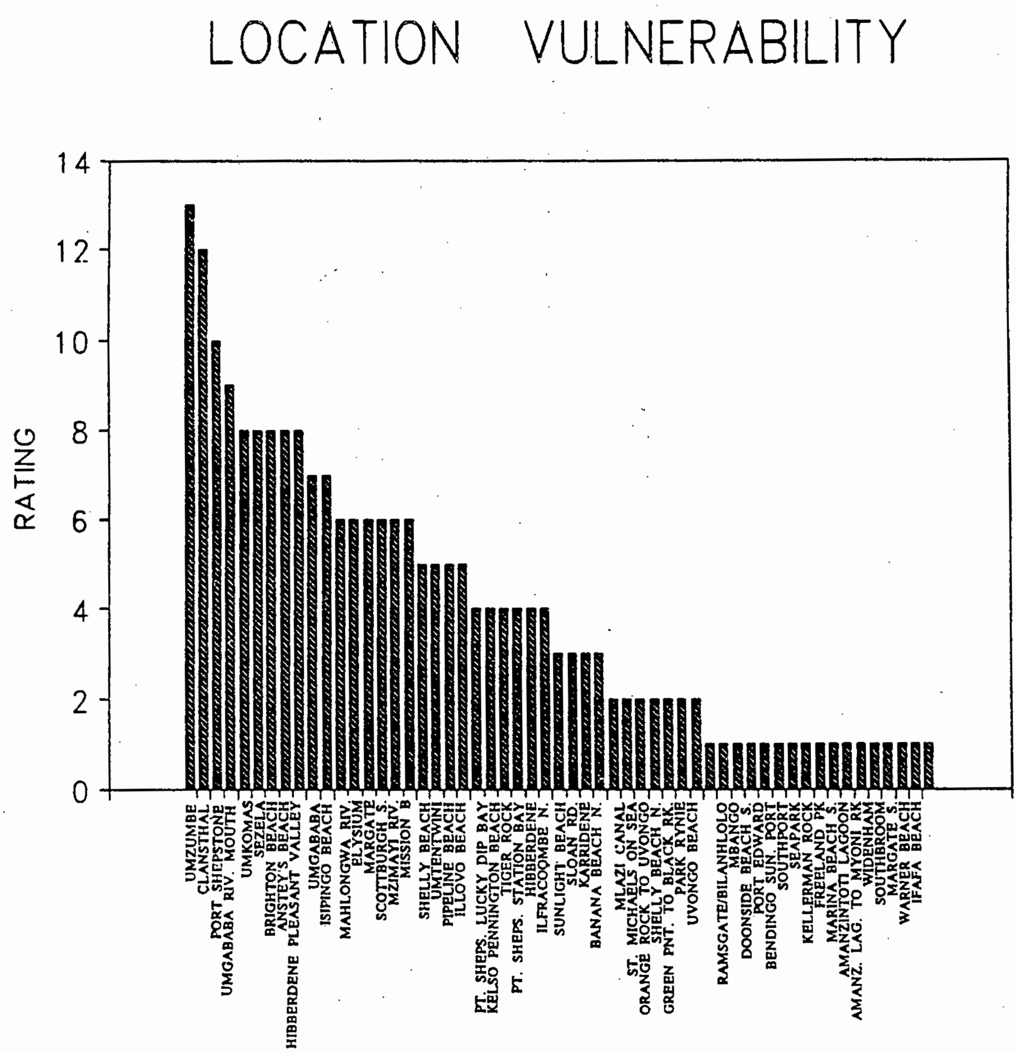


FIGURE 41. Relative location vulnerability along the Natal south coast.

TABLE 12. Locations on Natal south coast with zero risk rating to sea level rise

Ramsgate (north)
Empanjinti
Marina Beach, Kent Bay
Palm Beach
Trafalgar
Ramsgate, Mvutshinti river
Portobello
Ramsgate (south)
Munster
Amanzintoti (north)
Umbogintwini
Kelso, Station Bay
Mbambayani river to Scottburgh (south)
Winklespruit Beach
Doonside Beach
Amanzintoti to Doonside Beach
Pennington
Port Shepstone (south)
Oslo Beach
Uvongo Beach to Manaba Beach
Banana Beach to Bendingo Sandwich Port
Mtwalume
Woodgrange
Brighton Beach to Mlazi Canal

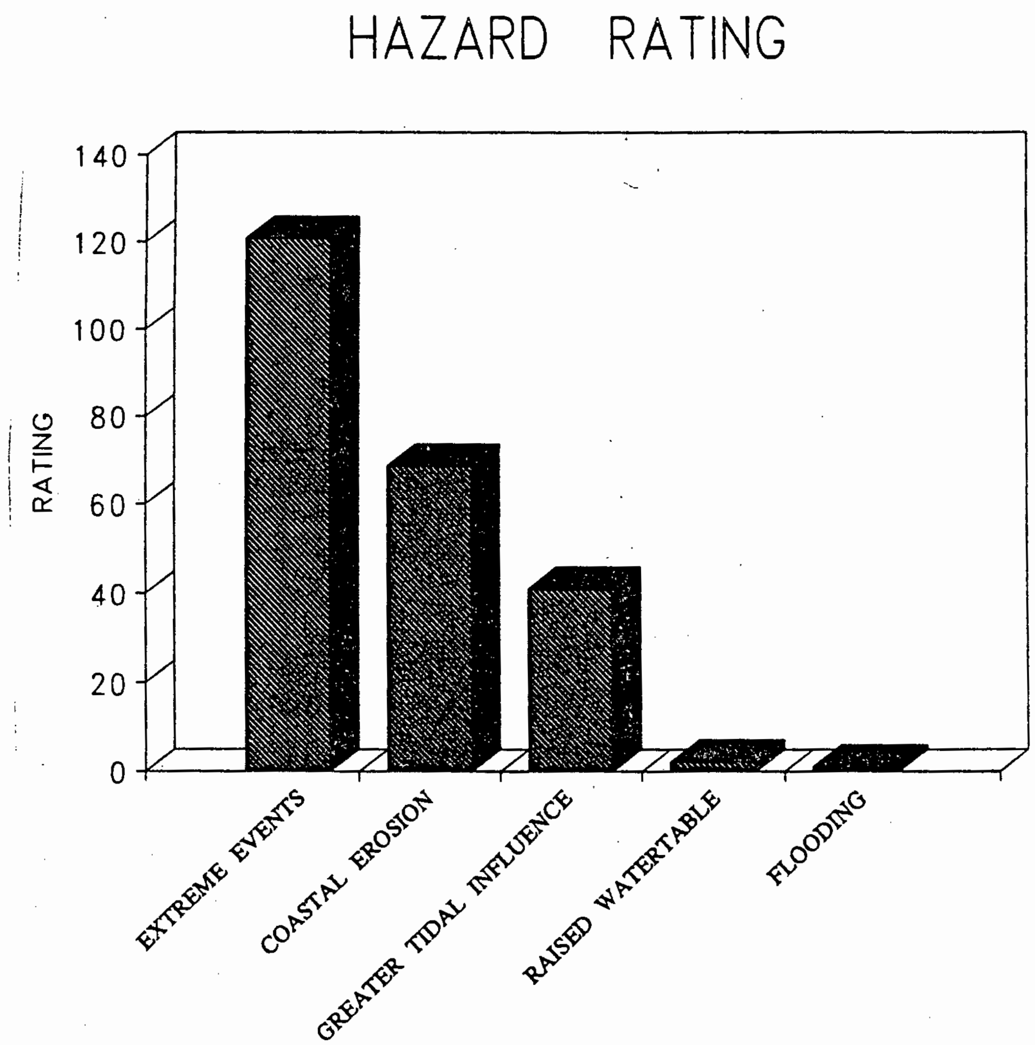


FIGURE 42. Relative hazard rating for the Natal south coast demonstrating those processes associated with sea level rise most likely to be detrimental to infrastructure and development.

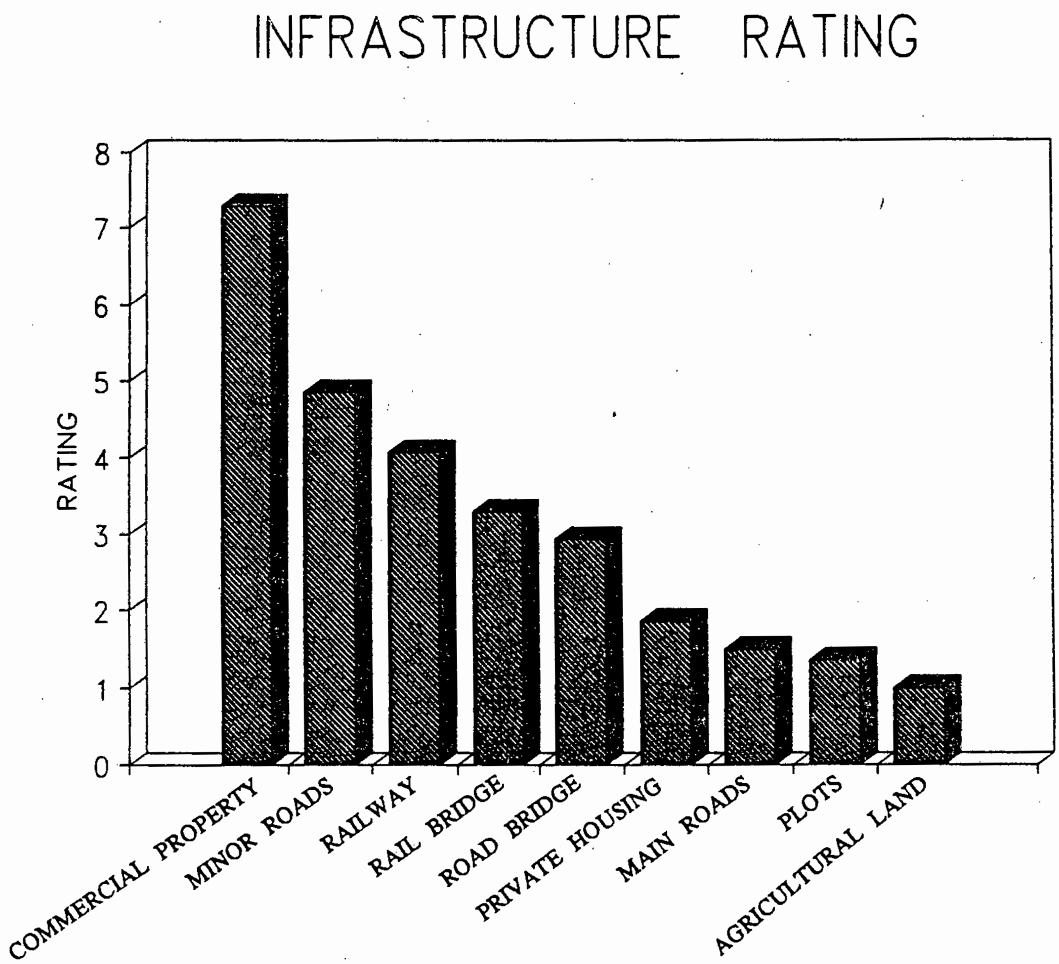


FIGURE 43. Relative infrastructure rating demonstrating which infrastructure and development categories are at greatest risk along the Natal south coast.

5.3:2 Discussion

No clear discernible pattern of location vulnerability can be drawn from Fig. 41. Umzumbe is a narrow beach at a river mouth with road and railways built on top of the spit at the mouth. The spit is poorly protected from an existing erosion (or stability) problem and is backed by a lagoon and low flood plain which will become inundated and subject to increased tidal action. Clansthal is a small privately owned beach development with houses on the HWM and railway embankments very close to HWM. Port Shepstone has a vulnerable spit on a river mouth on which the railway and road are built, and a number of municipal "services" and beach access points are at risk. If any general observation were possible, all that could be said is that those locations high up on the vulnerability index tend to have river mouths and coarse grained steep beaches, whilst those low risk areas tend to be open and pocket beaches. This is not unlike the Cape south coast where the most vulnerable locations are the estuaries, inlets and "tranquil retreats".

The hazard rating (Fig. 42) reflects the observation that most development is set back from the water level and only vulnerable to extreme events. The high scores indicate that a much broader spectrum of infrastructure is at risk than along the Cape coast. However, the fact that increased erosion seems to be the second greatest risk suggests that with time (allowing for increased erosion) the impacts of erosion and therefore extreme events, will become much more important. The rate of impact of sea level rise will therefore appear to accelerate. On the other hand, stabilization of the shore against increased erosion will control the rate of increase of impacts and any damage to infrastructure and property may be delayed. However, consideration must be given to a possible reduction in recreational suitability of beaches along this coast. This is a difficult parameter to quantify without detailed multi-disciplinary studies and has not been considered in this CVI. Hazards for the Natal south coast appear to have an erosion bias and those for the south Cape coast, an inundation bias. The Natal beaches are generally narrower than the Cape beaches and it would seem likely that recreational suitability of beaches will become an important criterion along this coast.

The infrastructure vulnerability (Fig. 43) reflects the pattern of development along this coastline. Those most vulnerable to sea level rise are the commercial properties - municipal pools, cafes and associated service roads which supply access to the beach areas. These structures are generally constructed with durability and cost in mind and if irreparably changed, would not constitute a major national shortcoming. However, the high vulnerability of the railway, its embankments and bridges, indicates a serious problem. Apart from commuters, this line forms a main service link for the sugar cane and agricultural industry of the area. Damage to the line would be detrimental to these industries and the cost of repairs, maintenance or re-location of the railway, would be considerable. In that respect sea level rise on the Natal south coast will have a national impact and it is submitted that an impact assessment for the railway be the subject for a study in its own right.

Unlike the southern Cape coast where the impacts will be first felt by private individuals, along this coast the impacts will be felt across a broader range of infrastructure and felt first on a municipal and national level. They may be felt later and may be slowed by shore stabilization programs, but when they start to occur (-i.e. when the erosion has reached a critical limit,) the rate of impact realisation will increase substantially.

5.4 Comparison of the Regional Vulnerability of the South Cape Coast and the Natal South Coast

Having determined the relative vulnerability of the two study areas by application of the Small Scale Coastal Vulnerability Index, the two regions may be compared. Each study area has its own characteristic vulnerability; that of the Cape coast tending to be more inundative and intrusional and the Natal coast more erosional in its risk. Within each region there would appear to be no obvious anomalies, such as, for example, a section of the Cape coast having an area exceptionally vulnerable to increased erosion. This supports the argument that major geomorphological boundaries have not been transgressed by the borders of the relevant study areas. A comparison of the two regions is therefore in order.

To achieve a comparison of the two areas the two sets of location vulnerabilities (Figs 37 & 41) may be combined directly, but the hazard and infrastructure ratings must be scaled by their relevant overall non-zero minimums. Appendix 3 contains the detail of the comparison. Figures 44 & 45 show the combined hazard ratings and infrastructure ratings. The combined hazard rating (Fig. 44) shows that although the relevant risks to each area differ, overall the south Cape coast has of the order of twice the risk assessed for the Natal south coast. Likewise, the development and infrastructure (Fig. 45) of the Cape coast is over twice as vulnerable as that of the Natal coast. There are clear morphological differences between the two study areas which can account for the difference in risk ratings:

- The southern Cape coast generally has a wide coastal plain, - the Natal south coast, a narrow one on which development is naturally limited.

- Rivers cutting the coast in the Cape tend to have lower gradients, lower banks and wider floodplains than their Natal counterparts.

- Cape rivers/estuaries/inlets are often associated with extensive backing wetlands or lagoons. This is not generally the case in Natal.

- Cape inlets have a greater tidal prism than most Natal counterparts although tidal range is very similar in both areas.

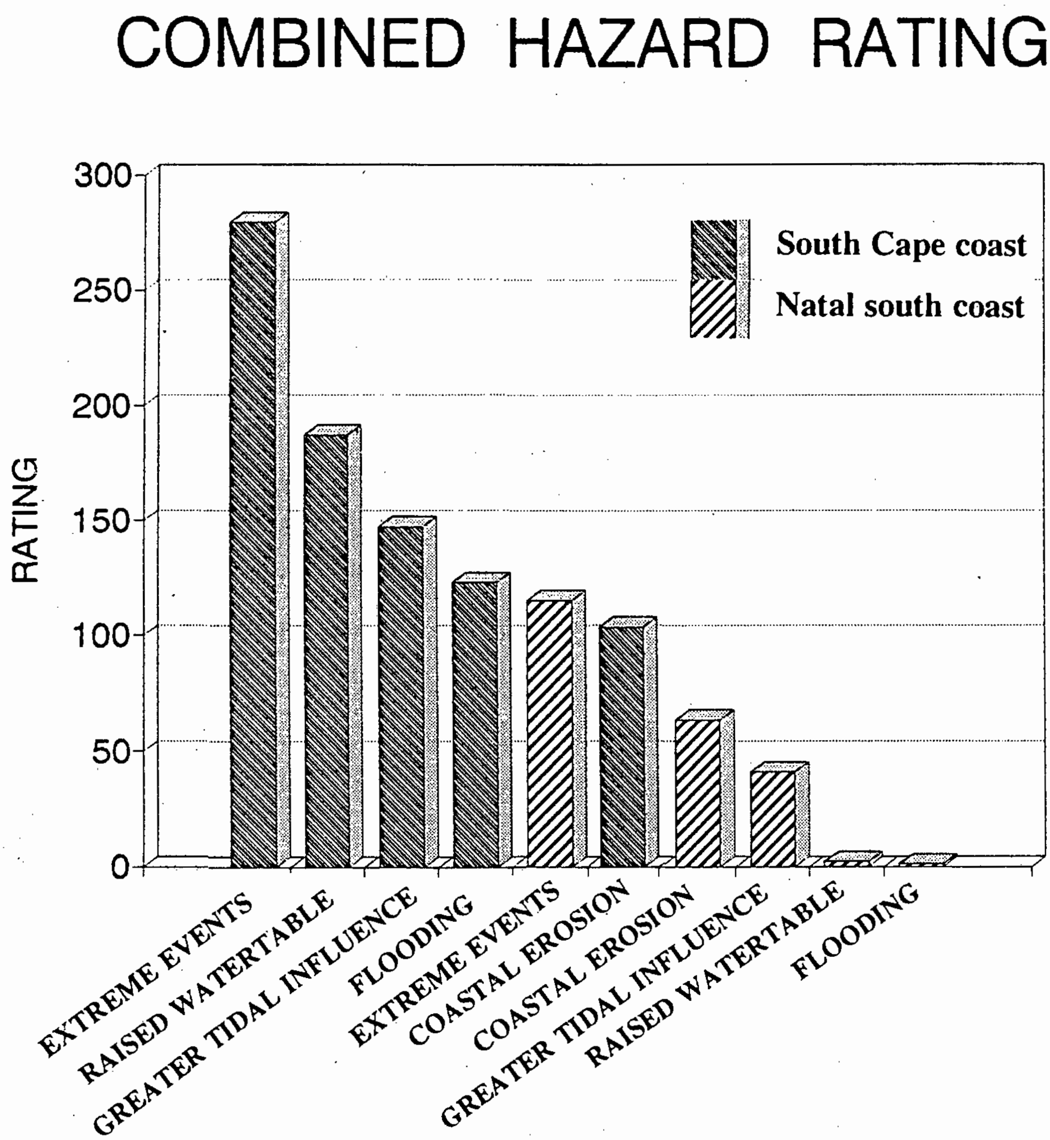


FIGURE 44. Combined relative hazard rating, south Cape coast and Natal south coast.

COMBINED INFRASTRUCTURE RATING

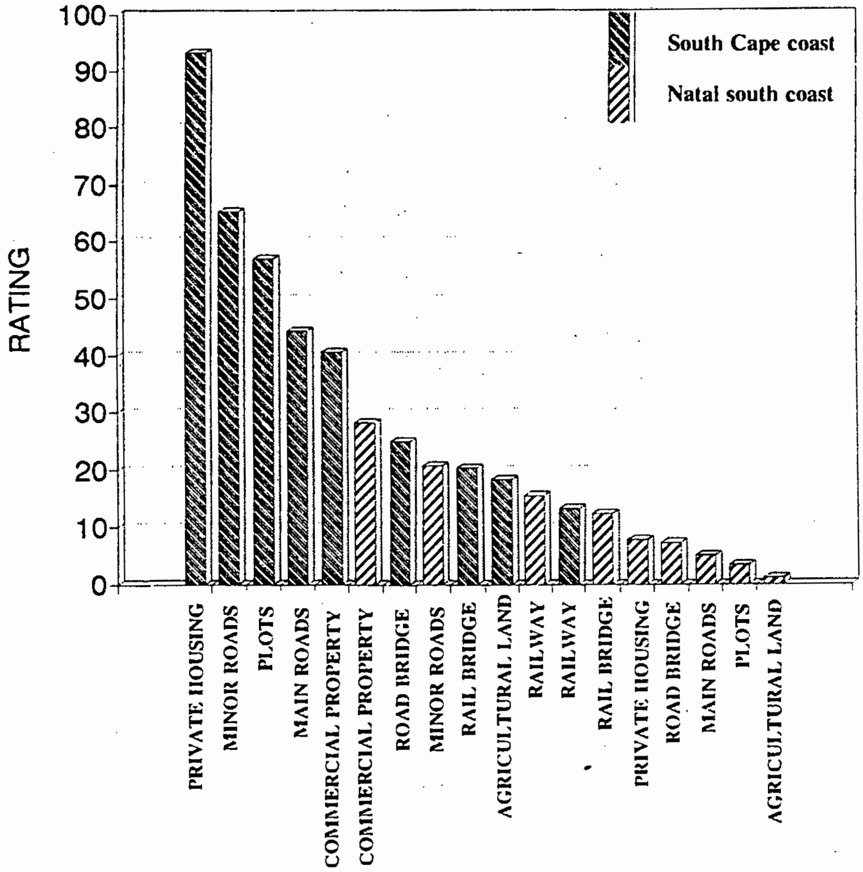


FIGURE 45. Combined relative infrastructure risk rating, south Cape coast and Natal south coast.

- Cape inlets are often well developed close to the waterline.
- Cape beaches tend to be wider, flatter and finer grained than Natal beaches, which also tend to have more rocky outcrops at low water.
- The Cape coast tends to have a larger wave climate.
- Development and infrastructure on the Natal coast is concentrated in a narrow coastal strip, closer in plan to the water level than in the Cape but normally at higher elevations.
- The general appearance of the Natal coast is that of a straight land margin that has experienced a period of rapid subsidence and marine transgression, the Cape coast contains more bays and inlets, and does not appear to have undergone rapid subsidence.

Despite the differences in coastline the application of the small scale or South African CVI (Hughes and Brundrit 1991a) is highly successful in determining where the impacts of sea level rise are going to be felt. In both cases the most severe impacts are associated with indentations in the coastline. In the Cape these "notches" are the estuaries/rivers mouths and inlets, often backed by wetlands and generally well developed for housing and industry. In Natal the "notches" are drowned river valleys and more importantly, the sandy spits at their mouths. Although saline intrusion and an increased tidal prism in these drowned channels is likely to have a limited impact on the system, the spits which often support the railway and coastal roads, will be subject to more direct wave action, extreme storm events and increased tidal currents. Ultimately these spits will tend to migrate (landward and along their length) and the infrastructure will be damaged.

As the impacts of sea level rise progress - those Cape inlets and shoreline developments will migrate landward and the land availability will allow for some partial absorption of the impacts with inundation effects being of greater consequence. The Natal south coast, with its narrow coastal plain and steep sided inlets and hinterland, will frustrate landward migration of developments which will gradually become more susceptible to increased erosion on the open coast. The first development to be affected will be the beach access points and railways and roads. The impact will therefore be felt on a municipal and national level - i.e. one which is able to cope with and manage these changes far better than a private individual can do, although the cost of these impacts will generally be larger.

Having identified inlets, estuaries and wetlands as being particularly vulnerable to sea level rise, a brief review of the application of the CVI shows that those "inlets" most vulnerable tend to have open mouths on a year round basis, low bed gradients, wide floodplains and low banks which are developed. Using a simple ranking based on these characteristics, a list of those "special environments" most vulnerable to sea level rise can be drawn up (Table 13). This type of environment is generally more prevalent in the south Cape coast and again reflects the tectonic history of the area.

TABLE 13. River mouths likely to be more seriously affected by sea level rise:

RIVER	LOCATION
Berg	Velddrif
Diep	Cape Town
Klein	Hermanus
Brëe	Witsands/Cape Infanta
Klein Brak	Mossel Bay
Groot Brak	Mossel Bay
Swartvlei	Wilderness
Krom	Francis Bay
Swartkops	Port Elizabeth
Kowie	Port Alfred
Keiskama	Hamburg
Umgeni	Durban
Mfolozi	St Lucia
St Lucia System	St Lucia
Kosi	Kosi Bay

The list is by no means exhaustive and is intended only as a guideline or focus for further attention. A detailed follow-up investigation of these special environments would be a worthwhile exercise to further predictions of the impacts of sea level rise.

The application of this vulnerability ranking method has provided a simple comparison of relative risk to sea level rise along separate stretches of coastline. Based on the impacts expected at "typical" or type environments (the case studies) the index provides a first order estimate of vulnerability but requires experienced operators. It is suggested that the application of this small scale CVI may be usefully employed, with sensible adjustments of the size of study areas (geomorphological regions), in other countries which may be lacking in data relating to historical shoreline changes and demography.

Chapter 6

DISCUSSION

The main objective of this thesis is to provide a first step towards managing the impacts of sea level rise by evaluating the possible impacts and recognising those most sensitive environments along the South African coast. To this end, a number of detailed case studies of the potential impacts were carried out in specific environments taken to be representative of the coastline, and the key processes in a South African context, identified. From the experience and results of the case studies, a regional impact assessment was developed which was used on a quasi-economic basis to evaluate some of the societal impacts of sea level rise. This small scale vulnerability index was applied to two geomorphologically contrasting regions and their vulnerabilities compared. The conclusions of the regional studies were then extended to the entire coastline to obtain a national vulnerability for which management options could be considered. This chapter discusses the steps taken to achieve this primary objective.

In order to discuss the success or failure of this study in portraying the key processes involved in this type of impact assessment, the general "typicality" of those locations chosen for case studies must first be considered. In all cases the impact assessments are carried out in urbanized areas in order to illustrate some of the societal impacts as well as the geomorphological changes that may be expected to accompany sea level rise.

6.1 Location typicality

Woodbridge Island and the Diep river system is a soft and moderately exposed coastline with some vulnerability to coastal erosion. The coast is backed by a wetland which, with higher sea levels, will become flooded to a tidal inlet and the channel and mouth characteristics may become modified. Much of the coast, inlet and mouth area is susceptible to extreme events. The wetland ecology is dominated by freshwater and is sensitive to human interference and salinity changes. Its aesthetic value and proximity to Cape Town has resulted in considerable development in the area and due to a lack of understanding of the sea level rise problem during the planning and development of this area, large sections of residential property and arterial roads are at risk to sea level rise. This risk will be perpetuated by future development unless cognisance of the impacts of sea level rise is taken.

The geomorphology and population/development pressure on this area is typical of many inlets and estuaries found along the South African coast and in particular the Cape coast. Of the Cape's fifty-three main rivers and streams, 77 % have soft or mobile mouths. Of those with soft mouths, 71 % are backed by vleis/wetlands/marshes or lagoons which will show a disproportionate flooded area : sea level rise relationship. Development in 62 % of these has already taken place in areas which may be susceptible to the impacts of sea level rise. This proportion of inlet-under-development can only be expected to rise in the future clearly qualifying this type of environment for "typicality" and further study.

The False Bay case study provides an example of a mixed hard and soft coastline with inlets and high population densities. The shore profiles suggest the potential for significant rates of increased erosion and only certain sections have sufficient buffer zone width or land availability to cope with future sea levels. A range of management options may be applicable but ribbon development (in the form of coastal roads) is clearly seen to be a high maintenance form of development which should be avoided in future. Typical of most open coasts, flooding and saline intrusion of the local aquifer is not a serious problem and in light of the population demand, groundwater engineering problems can probably be managed. The Marina development, exemplifying inlets on relatively open coasts, illustrates the vulnerability of these types of environments to storm flooding. The coastal railway close to the high water mark along much of the western seaboard also shows that even infrastructure on hard coastlines is not entirely immune to sea level rise.

This case study demonstrates the variability of impacts which can be expected along a mixed coastline and highlights some of the poorer planning decisions which have been made in the absence of effective coastal management policy. Of the locations assessed in the regional studies, 18 % of those along the south Cape coast and 25 % of those along the Natal south coast are zero risk rated. Extrapolating to the whole country, this suggests that the order of 75 to 80 % of all coastal towns will experience some level of impact from rising sea levels. The range of potential impacts demonstrated here shows that an adaptive and flexible response will be required.

The Durban case study typifies the heavily developed coastal city with fixed profiles and no room for buffer zones. It regards its beachfront as an enormous asset on which a large portion of the local economy is built and this asset is likely to change considerably or disappear altogether with rising sea levels. The use of changes in beach nourishment requirements as a proxy early warning system for sea level rise demonstrates the value of a knowledge of the background or baseline sediment budget. In addition, human alteration of the equilibrium profile may be responsible for even greater rates of erosion due to the creation of larger "active profile" widths. Interference with the natural profile shape should therefore be avoided. Again the vulnerability of inlets is stressed with reference to potential storm flooding of the Durban CBD as a result of the Umgeni river mouth breaking its banks. Engineering problems from groundwater are also of importance but the example typifies a case of high population pressures necessitating some type of remedial management procedure.
Examples of these type of impacts can be found in Cape Town, Mossel Bay, Port Elizabeth and East London and the majority of coastal tourist towns.

The Walvis Bay case study provides an example of an environment where some of the less obvious potential impacts of sea level rise can be extreme and other impacts are perhaps less than the natural variability of the system. Numerical modelling of coastal erosion produces a range of shoreline changes and again emphasises the importance of knowing the sediment budget. The magnitude of saline intrusion into the community's sole freshwater source demonstrates how freshwater extraction rates are likely to be of greater consequence than sea level rise. In many respects, the low lying nature of the town and surrounding country, its relative sheltering by Pelican Point and low population is analogous to many lightly developed estuaries/inlets with wide flood plains (like Rietvlei in the Diep river system case study C. 4). The extreme vulnerability of these types of environments to elevated groundwater levels and storm events is demonstrated and perhaps even caricatured in this case study.

This study is of relevance to all sections of low lying coast and vleis/lagoon systems.

6.2 Observations from the case studies

On a local scale, the impacts of sea level rise can be "pigeon-holed" for the sake of modelling, into those categories of:

1. Increased coastal erosion.
2. Increased flooding and inundation.
3. Increased salt intrusion and elevated coastal water-tables.
4. Reduced protection from extreme storm and flood events.

Although the relative impacts are site specific, a number of general observations regarding their modelling and effects can be made:

6.2:1 Coastal Erosion

The first and most obvious conclusion which may be drawn for the case studies is that all soft coastlines require "room" for landward migration of the profile and maintenance of the of the natural variability of the beach width. The landward migration is illustrated by application of the Bruun Rule (1962), but it must always be borne in mind that the indicated magnitude of profile migration is a "best estimate" obtained by use of a two dimensional model in a three dimensional application.

The case studies of Woodbridge Island and False Bay provide ample examples of locations where some form of development has taken place too close to the existing highwater mark. In these cases, the direct effects of increased coastal erosion will cause a loss of property or infrastructure or at very least, a sharp increase in their maintenance costs. In addition the Woodbridge Island case study shows the effects of the development on and break down of the primary dunes - the coastal-dwellers first line of defense against sea damage. Development on the dunes will eventually be seriously affected by sea level rise and any interference which may contribute to the breakdown or over-topping of the primary dune will expose a previously protected hinterland (in this case the west side of Milnerton town) to direct sea action.

In the event that the profile is not allowed to migrate, then the character of the beach and nearshore may alter dramatically. Reasons for the non-migration could include the presence of rocky outcrops which would "anchor" part of the profile, or the presence of some armoured development (usually) at the upper limit of the profile. Either way the profile will effectively be lowered and on a sandy shore would result in the loss of beach in-front of the seawall - as per the Durban case study, or a loss of the sandy portion of the beach - as per Strand and Gordon's Bay (False Bay). Not only will there be a pattern of change in use of these beaches from safe family/tourist beaches, to beaches which may be come unsuitable for recreational development but sea level rise produces a paradox. Development with its protection already within the active profile will, actually become more vulnerable to sea level rise by virtue of that protection holding the profile. However, on a positive note, an increase in longshore sediment transport rates or demand for beach nourishment (as at Durban) may be used as part of an early warning of gradual sea level rise, although actual sea level measurements are preferred.

With reference to Walvis Bay, this case study illustrates the dynamic nature of shorelines and implies that where the shoreline is too active/mobile/hostile for development then that shoreline is best left undeveloped and given a wide "safety margin". Consequently sea level rise on these types of coast will have little impact. Many modern coastal dunes around South Africa are active. Given that under certain condition nearly all are mobile then most coastal dunes must be considered hostile environments for development, especially in the face of rising sea levels.

Finally the case studies show that the effects of increased coastal erosion may have secondary impacts which may be far removed from the immediate site of interest. The break through to the river bend in the Woodbridge Island study exemplifies how coastal erosion may alter a channel's characteristics, thereby changing an inlet's tidal range. Both Durban and Walvis Bay studies demonstrate the value of knowing present sediment transport fluxes. Any change in these rates, either through human interference via construction, or natural via the exposure of natural "sediment traps", can produce significant changes in shoreline position which may be prohibitively expensive to rectify. Longshore sediment transport rates should therefore be monitored to indicate impending coastal management problems.

6.2:2 Flooding & Inundation.

The presence of coastal dunes, high beach berms or rocky outcrops around most of the coastline of South Africa ensures that except for extreme cases (e.g. Walvis Bay), the impacts of flooding and inundation on the open South African coast will be negligible in comparison with those of coastal erosion. Even in the extreme case of Walvis Bay, flooding and inundation of the open coast will be of little significance as the vulnerable areas form part of an extremely dynamic sedimentary environment, too harsh and unstable for development. However, the effects are very important in those sheltered environments where the effects of wave erosion may be ignored. In these environments (i.e. vleis, lagoons estuaries) the tidal prism may be expected to increase with rising sea level and the size of the increase will be related to the steepness of the inlet's banks. Flooding in the sheltered environment will occur at least to the level of the new MSL in the open water with obvious consequences for everything below this level. The tidal range within the flooded area will be a function of the characteristics of the channel which leads to the flooded area. The Woodbridge Island case study provides a good example of the increase in internal tidal range that may be achieved by reducing the resistance to water movement in the channel - i.e. shortening, deepening or widening the channel. However, a useful observation for planning purposes is that knowing the flooded area below the elevation of any new MSL, the channel dimension which would support a certain internal tidal range may be easily calculated. Planning decisions for these sheltered environments may therefore be made well in advance of rising sea levels. Perhaps channel dimensions could be set or fixed at an early stage, thereby fixing the internal tidal range (and maximum area flooded at MHWS) in order to facilitate some of the development.

Subsequent to the increase in tidal prism of these sheltered environments, the volume of the flood tidal delta in the inlet will be expected to increase. In doing so the efficiency of the inlet's natural sediment bypassing process will be reduced and increased coastal erosion of the downdrift side of the mouth may be expected. If the mouth is not fixed this may increase the rate of mouth migration, a process that in some cases may already be occurring at a significant rate. Development adjacent to inlet mouths (e.g Woodbridge Island) may be therefore become more vulnerable with rising sea levels. As a precaution coastal planners should consider expert opinions before considering these areas for development.

6.2:3 Saline Intrusion

The extent of saline intrusion into inlets is a function of channel slope and river flow and is obviously very individual and variable throughout the year. Increased intrusion into coastal aquifers may be modelled using topographic relationships (as per Walvis Bay and False Bay studies) and is generally expected to be of limited significance unless freshwater draw points are located very close to the shoreline. In developed areas the extent of saline intrusion into an aquifer is more likely to be governed by freshwater extraction rates than sea level rise.

6.2:4 Raised Water-Tables

Coastal water-tables under undisturbed conditions will rise by approximately an equivalent amount to sea level rise. In many areas this may cause engineering and waterlogging problems particularly around inlets and wetlands. However the water-table, if fresh, can usually be managed on the open coast using existing technology but around inlets with low population densities, the demand, magnitude and cost of the problem may not warrant management programs. As for the description of saline intrusion, the increase in groundwater levels on the open coast is more likely to be governed by freshwater extraction than rising sea levels. However, if the water-table is marine, as at Walvis Bay and some channel bars in Cape estuaries, then its management will be prohibitively expensive if indeed possible. In the case of developed channel bars and islands in estuaries, the water-table may rise through the surface or to a level of inconvenience even if shore protection work has been carried out. Development of these sites should not therefore be carried out without specialist engineering supervision.

6.2:5 Storm Vulnerability

Storm flood levels may be successfully modelled by the combination of storm surge on the new MHWS and wave set-up for design period storm waves on that shore. Storm surge return periods may be determined from hourly tide gauge data (Searson *in prep.*) or may be estimated where records are of insufficient length. With rising sea levels the effective protection of existing coastal defenses will be reduced as smaller storms will be capable of over-topping them.

Surges and larger wave set ups are generally of sufficient duration to enter into sheltered inlets, estuaries and embayments where their effect will be most greatly felt. In addition the deeper water/greater tidal prism in an inlet may reduce the protection afforded by the inlet's mouth. Small rises in sea level can therefore dramatically increase a sheltered location's vulnerability to extreme sea storms (e.g. Marina da Gama, False Bay case study). An increase in storm damage in inlets and on the open coast may therefore be one of the earliest indicators of rising water levels.

The effects of storm induced erosion are site specific and may be modelled with a moderate degree of confidence (e.g. Swart 1974, CSIR 1986). Except for one case study, storm erosion has not been modelled but its potential must be considered in all coastal management projects.

6.3 Development and observations of the Coastal Vulnerability Index

From the case studies an understanding of the critical processes accompanying sea level rise in the South African context was obtained which could then be applied to the coast on a more general or regional scale. It was clear that the original four categories of impacts used in the case studies was too vague when considering the secondary effects of channel exit modification due to flooding and inundation. Therefore, the category of increased tidal influence in inlets (e.g. increased tidal currents) was introduced for a broader impact assessment.
The effect of increased saline intrusion was not considered for the CVI due to a lack of detailed understanding of the hydrodynamics of all the coastal aquifers and estuaries in the country and the likelihood that the impacts will be very localized. In any case freshwater extraction rates in aquifers will probably have a greater effect on the position of the saline interface than the predicted range of sea level rise.

A previously documented coastal vulnerability index (Gornitz and Kanciruk 1989) which was intended for global application, was found to have too coarse a resolution for detailed application in the South African environment. Its relief component is too coarse to pick up high risk narrow coastal plains. Its geological classification has no structural component and ignores rock mass competence and its range of landforms is not suitable for the relief scale chosen. Tidal range around the whole coast is micro- to meso-tidal and South Africa has an extremely high wave energy climate. Finally, the South African knowledge of relative sea level changes and shoreline displacements is poor, particularly on the east coast which has a high population density. This parameter can only be used selectively and is therefore not totally reliable. The index can however be used to suggest areas worthy of further study and much of the South African coastline is highlighted in this way.

As a result of these shortcomings a small scale CVI was developed (Hughes and Brundrit 1991a) which takes into account observations more applicable to South Africa. It is a quasi-economic impacts assessment and is better suited to determining the societal impacts of sea level rise. This CVI was applied to the Cape south coast and Natal south coast.

The south Cape coast application revealed the most vulnerable areas to be those surrounding estuaries, lagoons and tidal inlets (i.e. Woodbridge Island/Rietvlei type environments). The greatest hazards overall are from extreme storm and flood events followed by waterlogging/raised water-tables and greater tidal action in the inlets, with increased coastal erosion being the slightest risk. These impacts will most affect the private housing sector with infrastructure of national importance being relatively much safer. In general the impacts tend to be inundative in character with storm flood levels aggravating the situation. This is a result of the general morphology of the Cape coast's wide coastal plains and shallow sided inlets which allow for a non-linear relationship between increments in sea level and area flooded in inlets. In these sheltered environments development has often been carried out with only a small safety margin above water levels and the possibility of an extraordinary event occurring is deemed an acceptable risk. Small increases in sea level dramatically alter the storm water level return frequencies and it is likely therefore that the impacts will be felt in this region after only a relatively small sea level rise.

The Natal south coast - a highly developed, narrow coastal strip - revealed a different set of results on application of the small scale CVI. Determination of the most vulnerable locality type was unclear although there was a tendency towards sites at river mouths with spits being the highest risk. The greatest hazard was from extreme events followed by the risk due to increased erosion and greater tidal influence (at river mouths), with elevation of water-tables and flooding being of insignificant impact. In examining the infrastructure at greatest risk, it is clear that those commercial and municipal properties (i.e. cafes and swimming pools etc.) served by minor roads and car parks which provide nodal access to the beach areas, will be the first to be affected. Next at risk is the coastal railway (which often crosses the river mouth spits) then railway bridges with the risk to private housing falling well down the list.

Along this section of coast the beaches are generally quite narrow but backed by high, well vegetated dunes on which the development is often found. Dune protection programs are in place in many locations. The amount of increased erosion likely to be caused by a relatively small increase in sea level is low as a result of the steepness of the profile and presence of nearshore rocks. It probably falls within the range of most beaches' natural variation. Consequently the Natal south coast will require a larger rise than the southern Cape coast before any appreciable erosional impacts will be noticed. However, once a certain threshold level of erosion has occurred the risk to extreme events and further erosion will become much more evident. Note that in many river mouth locations these erosional impacts may be exacerbated by increased tidal action.

The overall implication for the Natal south coast is therefore that a larger rise in sea level will be required (than the Cape coast) before any serious impacts manifest themselves. When they do they will be felt first on a municipal level and then on a national level with possibly serious consequence for the sugar and agricultural industries. The impacts will tend to be more erosive in nature and the narrowness of the beaches and presence of the railway will make it difficult to avoid the use of hard structures to protect the shores. This will undoubtedly change the characteristics of the beaches, probably detracting from their suitability for recreational purposes. As a result of the increasing unsuitability of certain beaches, development pressures and the tourist industry may also be expected to change.

Although not overly clear in the Natal case, there is an overall tendency towards high vulnerability in inlets and estuaries. The question therefore arises - what makes inlets so vulnerable? Vulnerable tidal inlets, especially in the Cape, are found on wide gently sloping coastal plains and generally have low banks and wide flood plains with relatively infrequent flooding. As the majority of these inlets are sheltered and desirable locations for either housing development or industry, development has taken place in many to within a narrow margin of the inlet's surface and groundwater levels. In many instances development has taken place on low mid-stream channel bars and islands which could probably be easily remobilized and even if shore protection work were to be carried out, waterlogging from raised water-tables is still likely to occur. In addition, a larger tidal prism in the inlet will increase tidal currents and reworking of spits and channel banks which often support considerable development (e.g. Keurbooms River mouth, Plettenberg Bay), may occur. Of possible greater consequence is that higher mean sea levels and greater channel depths will reduce the inlet's protection from storm surges thereby increasing the level of storm damage. Marine and fluvial deposition may attempt to rebalance the sediment distribution and raise the channel/mouth but the rate at which this rebalancing will take place

(if at all) is unknown for most inlets. The likelihood of an extreme event occurring before re-adjustment must therefore be considered seriously.
In examining the two "sets" of "responses" to rising sea levels the environmental factors which institute a difference are the width and slope of the coastal plain, the annual rainfall/catchment geology and flood frequencies of the rivers and the beach grain size. Wide, gently sloping coastal plains, characteristic of the Cape south coast, allow the development of gently sloping and meandering rivers and estuaries with correspondingly wide flood plains, moderately stable channel bars and low banks. Many of these estuaries have a long tidal reach. Small increments in sea level will therefore have an exponential effect on areas of land waterlogged, flooded and inundated. Narrow, steep coastal plains with high river gradients and banks will conversely have a much lower sea level rise : wetted area relationship. In addition, wide coastal plains provide plenty of room for development to take place, unlike the narrow coastal plains which tend to concentrate development along the coastal margin as in the Natal south coast.

Complementary to the coastal plain dimensions, large catchment area or large (flood) volume rivers with steep gradients, characteristic of the Natal south coast, tend to have steeply incised channels and banks with narrower flood plains. Bars are poorly developed. Development is not possible on steep banks or valley sides and is therefore located at a comfortable distance away from the water surfaces. Again there will be a low sea level rise : wetted area relationship.
Along the Natal coast the combination of sediment availability, wave and wind directions, tend to allow the development of large well vegetated dunes topping the beaches. Although the beaches are generally coarse grained and therefore tend to be more mobile, the size and vegetated stability of these dunes will tend to act as a good buffer zone to increased erosion. However, in places along the Natal south coast, development has tended to take place on these dunes, which have on occasion been bulldozed flat, and the long term efficacy of the buffer zone has been reduced.

Environments around the South African coast which should therefore be deemed sensitive to sea level rise include all inlets, their channels, mouths and islands, low lying coastal vleis and exposed coastal dunes and foreshores where development has taken place within 150 m of the HWM. These types of environments require further detailed site specific study before any land use proposals can be considered.

6.4 National Vulnerability to Sea Level Rise

In order to determine the national vulnerability of South Africa to the rising sea levels, the conclusions of the two regional studies must be applied to the whole coastline. The direct comparison of the two regions (C 5.4), shows that overall the south Cape coast is much more vulnerable than the Natal south coast but more importantly, provides a broad scale on which to compare vulnerabilities. These comparisons and conclusions can be used to determine the likely response of any region, based on its geology, morphology and rainfall. The coastline may then be divided into handy sized units of similar expected response:

- The Cape west coast has a wide coastal plain and is likely to respond in a similar fashion to the Cape south coast except the higher aridity and deeper water-tables are unlikely to create such "raised water-table" problems. Increased saline intrusion may, on the other hand, become more important with future climate change and increased aridity in this area. Many of this coast's inlets are blind or at least closed for long periods through-out the year. With higher water levels these will become more tidal and may remain open for longer, creating more extensive lagoonal/wetland habitats (possibly suitable for certain wildfowl) where unrestricted.

- The Cape south coast, south-east coast and part of the eastern Cape coast have wide coastal plains of similar elevation and will probably respond like the south Cape coasts regional study. Tidal inlets will the most vulnerable environments as a result of reduced protection from extreme events, flooding and inundation, raised water-tables and increased tidal influence. Towards the eastern section, the coastal plain narrows and becomes more elevated. Here the "typical" Cape south coast response will become replaced by the Natal south coast response.

- The eastern Cape coast, north of about Port Alfred, through the Ciskei and Transkei coasts to about Southbroom in Natal, may be expected to respond in a similar fashion to the typical Natal south coast response. This is a function of the general ruggedness of the topography of much of this coast and its high and very narrow coastal plain.

- From Southbroom to approximately Ballitoville, north of Durban, the narrowness of the coastal plain, high rainfall, flood frequencies, steep sided inlets and large vegetated coastal dunes suggest that all this coast will have a similar response to the Natal south coast regional study. The highest risk along this section of coast can be attributed to extreme events and erosion on the open coast and inlet mouths. The impacts are therefore generally more erosional than inundative in process.

- North of Ballitoville the coastal plain starts to widen but remains quite well elevated above MSL. Rainfall and flood frequencies remain high and although the inlets and estuaries tend to have wider flood plains, their banks are usually deeply incised. The presence of these inlet features together with the high, well vegetated coastal dunes suggest that this area will have a similar response to that of the Natal south coast regional study. However, there are some notable exception to this response which include the Umfolozi/St Lucia system and the Kosi Bay system where the response will be more similar to the Cape south coast.

When reviewing the impacts of sea level rise in the South African context, population pressure must be seen to be an additional, if not the overriding factor governing the societal impacts of sea level rise. In comparing the similar response units above with the country's population distribution, it is clear that the attractiveness of a region for habitation or development tends to overlap with many areas that have a high vulnerability to sea level rise. Fig. 46 shows the population density of South Africa but it must be noted that these statistics predate the rapid urbanization that has occurred since about 1985. Townships and areas of informal housing such as Khayalitsha near Cape Town (estimated pop. ± 400,000) and Inanda and Umlazi near Durban (estimated pop. ± 500,00 ea.), have mushroomed in areas previously barely populated, and are not represented here. This rate of urbanization is expected to continue with populations in the metropolitan areas of Cape Town, Port Elizabeth, George and Mossel Bay more than doubling their 1980 levels by 2010 (Urban Foundation, 1990). The Durban metropolitan area is expected to triple its population in the same period (Urban Foundation, 1990). Any attempt to establish a national vulnerability without cognizance of the population dynamics and factors governing the distribution would therefore be incomplete. A combination of sea level rise impacts and population pressures must therefore be considered for national vulnerability. Figs. 47a,b and c provide the most useful means of combining these factors and conveying national vulnerability. The findings are summarized in Table 14.

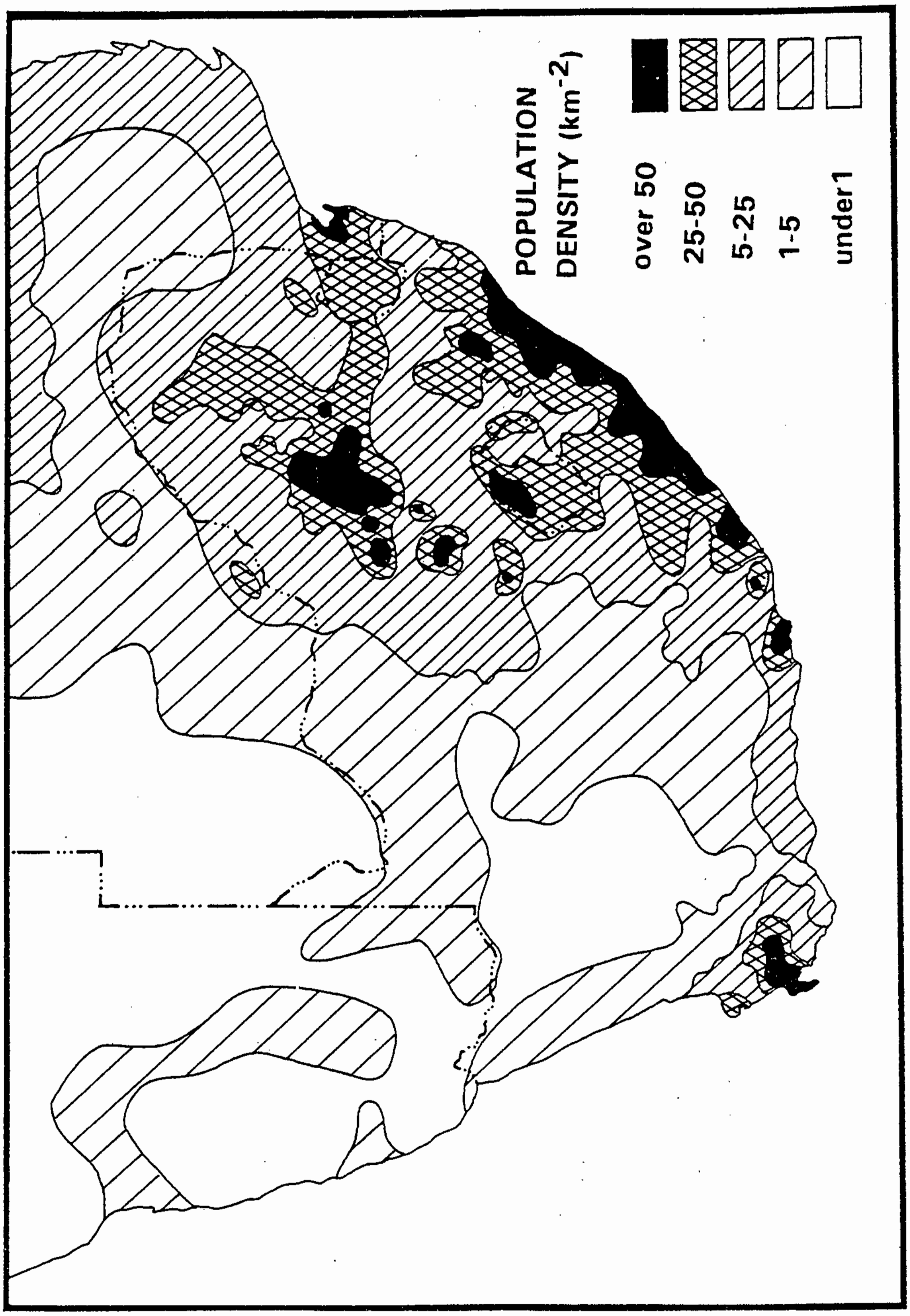


FIGURE 46. South African population distribution (after Philips 1979).

A
Overall very low risk to rising sea levels. Low population density, wide coastal plain, significant longshore sediment transport. General shortage of freshwater may make isolated developments vulnerable to saline pollution in aquifers etc. Small developments around river mouths may become more vulnerable to flooding, increased tidal influence & storm events, e.g. - Port Owen, Berg river

B
Low population density, hard coastline and low overall risk. Small sandy coves and beaches interrupted by rocky outcrops and headlands. Rocky platforms at LWM will tend to slow present eroding status of shore although not change status. Developments are usually small holiday cottages well set-back from the shore.

C
Sheltered lagoon environment with private housing/holiday homes close to water level and waters edge. Vulnerable to raised watertable,flooding and storm events especially towards southern east shore. Dev close to tidal channel along this shore and may become more susceptible to increased tidal influence/erosion.

D
Low risk, low population density area with large coastal dunes and poor access to the shore

E
High risk area see detail of Fig. 48.

F
Mostly hard coastline with low overall risk. Developments at mouths of Bot and Klein rivers may become vulnerable to flooding, greater tidal influence, raised water tables and extreme events.

G
Low population density, poor access and a mixture of hard coast with sandy coves, bays and some dunefields make this a low risk area. Holiday dev at mouth of Brëe and Kafferkuils rivers may become slightly vulnerable to increased tidal action although river banks are quite steep. Increased saline intrusion to Brëe may affect agricultural water supplies. Stillbaai seafront may see an increase in erosion and will feel more storm damage.

H
High risk area see detail of Fig. 49.

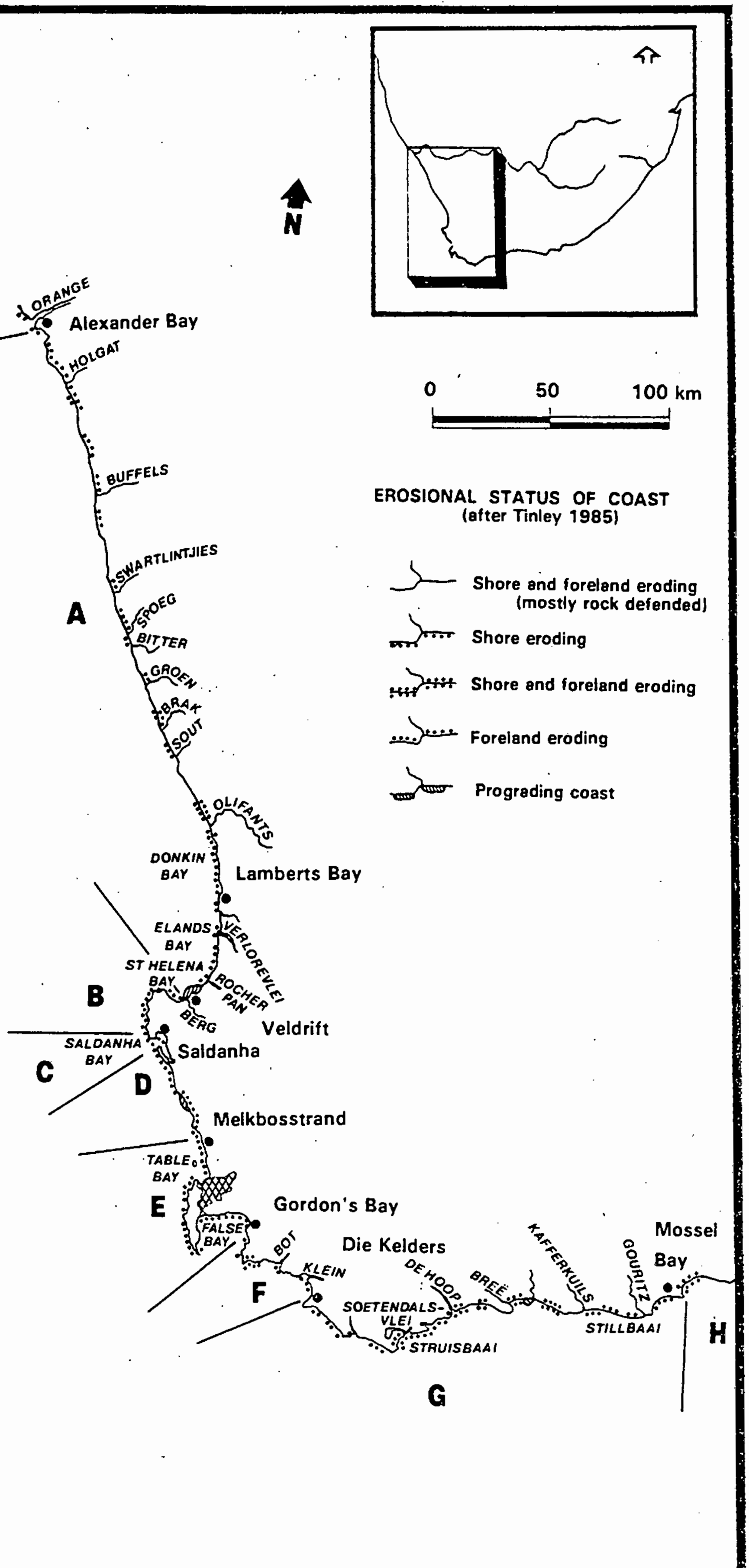
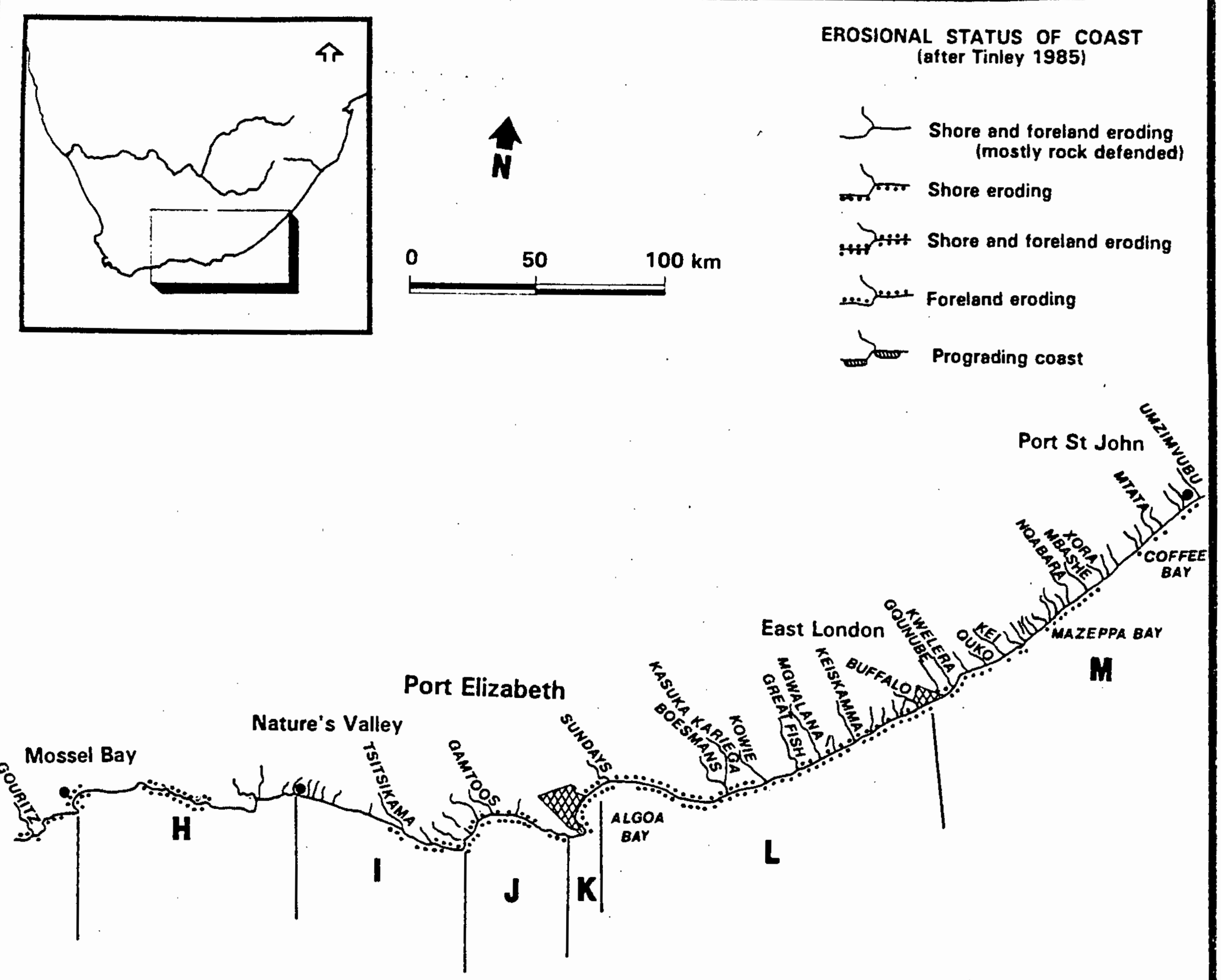


FIGURE 47a. National vulnerability of South Africa to sea level rise.



I
Hard , high relief coast with zero population. Low risk.

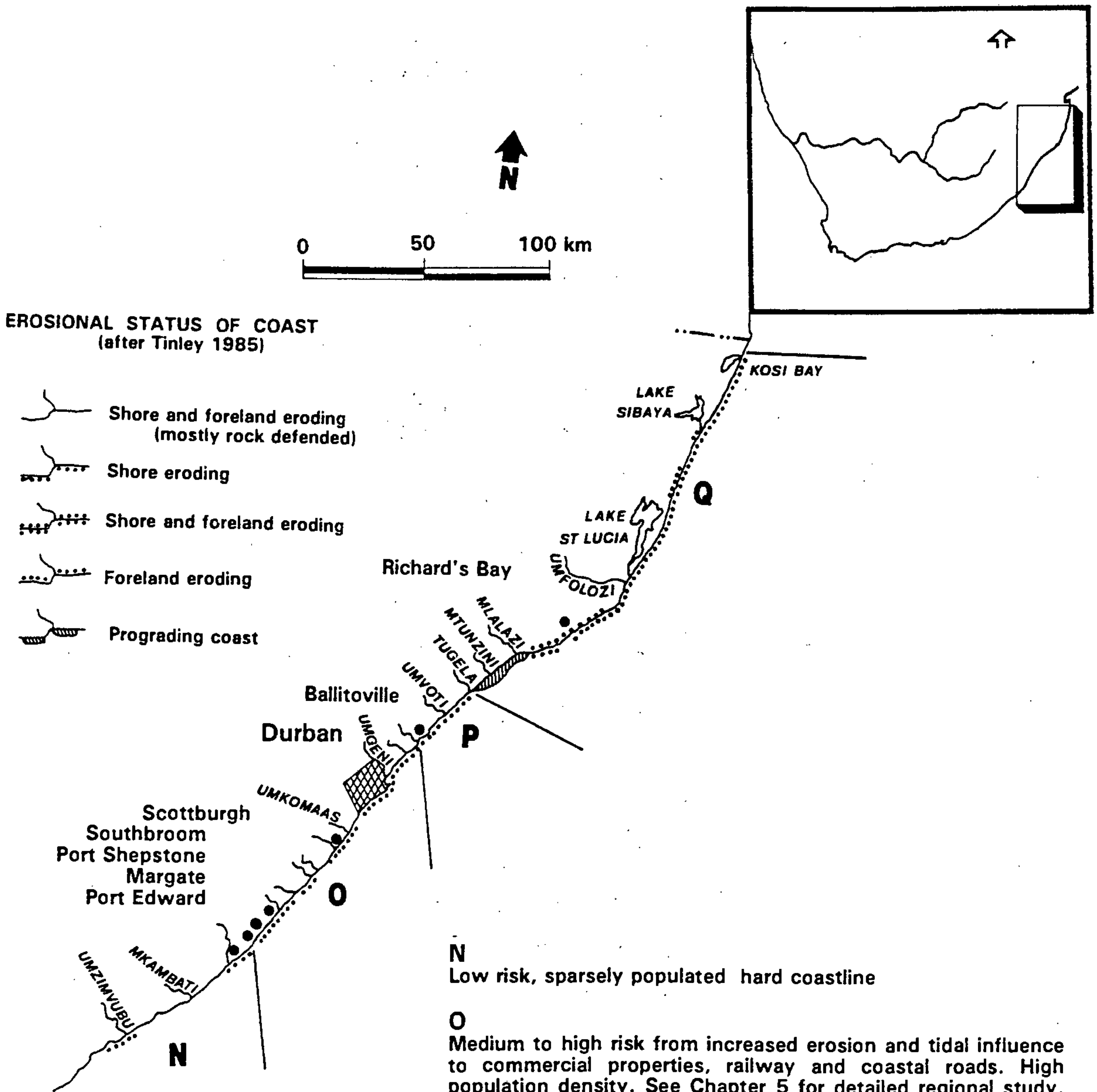
J
Medium low risk. Med. to low population density centred in small coastal towns e.g. Jeffreys Bay, Sea Vista on Krom river, where risk to commercial property, private housing and small roads may be slight due to increased erosion, tidal influence and a certain amount of flooding

K
High population density, high risk. Major roads, commercial property and private housing at risk to increased erosion (e.g. main coast road north), flooding, raised water tables and storm damage - especially in Swartkops river.

L
Medium to low erosional risk overall due to low population densities, high coastal dunes and increasing relief eastwards. Development around Kowie (Port Alfred) and Buffalo (East London) may be at risk to raised water tables (esp. Kowie), flooding, increased tidal influence and storm events.

M
High relief, hard coastline with low population density and development located mostly around river mouths. Vulnerability will be very localized and probably felt most at rural housing level. However, increases in flushing of some estuaries may be expected to improve water quality.

FIGURE 47b. National vulnerability of South Africa to sea level rise.



N
Low risk, sparsely populated hard coastline

O
Medium to high risk from increased erosion and tidal influence to commercial properties, railway and coastal roads. High population density. See Chapter 5 for detailed regional study. Durban CBD at particularly high risk to extreme events, see Chapter 4 case study

P
Med. to low population density. Small holiday developments may be at slight risk to erosion or increased tidal influence around river mouths. Large well vegetated coastal dunes provide good buffer zone

Q
Low population density and low overall risk. High well vegetated coastal dunes, beach rock and rocky platforms will tend to reduce magnitude of erosion. Mhlatuzi, Mfolozi, St Lucia and Kosi Bay systems may experience increased tidal influence, but where present, development is generally well set back although some agricultural land may be at risk to flooding. Kosi system will probably undergo significant biochemical changes with an increasing marine influence.

FIGURE 47c. National vulnerability of South Africa to sea level rise.

TABLE 14. NATIONAL VULNERABILITY TO SEA LEVEL RISE.

REGION, ENCOMPASSING SENSITIVE LOCATIONS	OVERALL RISK	POPULATION DENSITY	COASTAL PLAIN WIDTH	MOST LIKELY HAZARDS	MOST LIKELY RISK INFRASTRUCTURE
ORANGEMUND TO VELDRIFT	VL	L	W	(GW POLLUTION). (F).	(PH). (MIN). (COM).
- VERLOERNVLEI RIVER	L	L	W	F. (T). (GW POLLUTION).	(AGR). (PH).
- OLIFANTS RIVER L	L	W	F. T.	(PH).	
- GROOT BERG RIVER	L	L	W	F. T.	PH. COM. AGR.
VELDRIFT TO SALDANHA	L	M/L	N	(E).	(PH).
SALDANHA TO LANGEBAAN	M	M	W	GW. F. (E).	PH. (COM).
LANGEBAAN TO MELKBOSSTRAND	L	L	W	(GW) (E)	(PH)
MELKBOSSTRAND TO GORDON'S BAY	H	H	N & W	F. T. E. GW.	PH. COM. MAJ.
- DIEP RIVER	H	H	W	F. T. E.	PH. (MAJ).
- SANDVLEI /MUIZENBERG	H	H	W	F. T. E.	PH. COM. MIN.
- ZEEKOEVLEI	H	H	W	E F T	MAJ. COM.
GORDON'S BAY TO DIEKELDERS	L	M	N	(E).	(PH).
- BOT RIVER	M	M/L	W	F. T. GW.	(PH).
- KLEIN RIVER	M	M/L	W	F. T. GW.	(PH).
DIE KELDERS TO MOSSEL BAY	L	L	W	GW. T.	(PH).
- BREE RIVER	L	M/L	W	GW. T.	(AGR).
- KAFFERKUILS (STILBAAI)	M/L	M/L	W	GW. F. T.	PH. (AGR).
MOSSEL BAY TO NATURE'S VALLEY	H	H	W	F. T. GW. E.	PH. MIN.
- VOORVAAI	H	H	W	E.	COM. PH.
- KLEINBRAK RIVER	H	H	W	F. T. GW.	PH. MIN.
- GROOT BRAK	H	H	W	F. T. GW.	PH. MIN.
NATURE'S VALLEY TO CAPE ST FRANCIS	L	L	N	(GW). (E).	(PH?)
- KROM RIVER	M	M/L	W	T. F. E. GW.	PH. COM.
CAPE ST FRANCIS TO PORT ELIZABETH	M/L	M/L	W	E. T. F.	(PH).
- SEEKOERIVER	M/L	M/L	W	T. F. GW.	(PH).
PORT ELIZABETH	M/H	H	W	E	MAJ. COM.
- SWARTKOPS RIVER	H	H	W	GW. F. T.	PH.MIN.
PORT ELIZABETH TO EAST LONDON	M/L	L	W	E. F. T.	PH.
- PORT ALFRED	H	M	W	GW. F. T.	PH.
- BUFFALO RIVER (E. L.)	H	M	W	GW. F. T.	PH. (COM?)
EAST LONDON TO SOUTHBROOM	L.	L.	N.	(E?)	(PH?)
SOUTHBROOM TO BALLITOVILLE	M/H	H	N	E. T.	COM. MIN. RAIL
- UMGENI RIVER	M	H	W	(F) (T) [N.B. EXT. EVENT]	(COM)
BALLITOVILLE TO TUGELA	L	M	N	(E.) (T)	COM. MIN.
TUGELA TO KOSI BAY	L	L	W	(E?) (T?)	?
- MHLATUZE RIVER	M	L	W	(F) (T)	?
- MFOLOZI /ST LUCIA SYSTEM	M	M/L	W	(F) (T) (GW)	?
- KOSI LAKES SYSTEM	M	L	W	(F) (T)	?

KEY:

H. HIGH	GW. GROUNDWATER	PH. PRIVATE HOUSING
M. MEDIUM	F. FLOODING	MIN. MINOR ROADS
L. LOW	T. INC. TIDAL INFL.	COM. COMERCIAL PROPERTY
W. WIDE	E. EROSION	MAJ. MAJOR ROADS
N. NARROW		AGR. AGRICULTURAL LAND

6.5 Identification of Particularly Sensitive Localities

In examining Figs. 47a, b and c four regions are identified as being particularly sensitive:

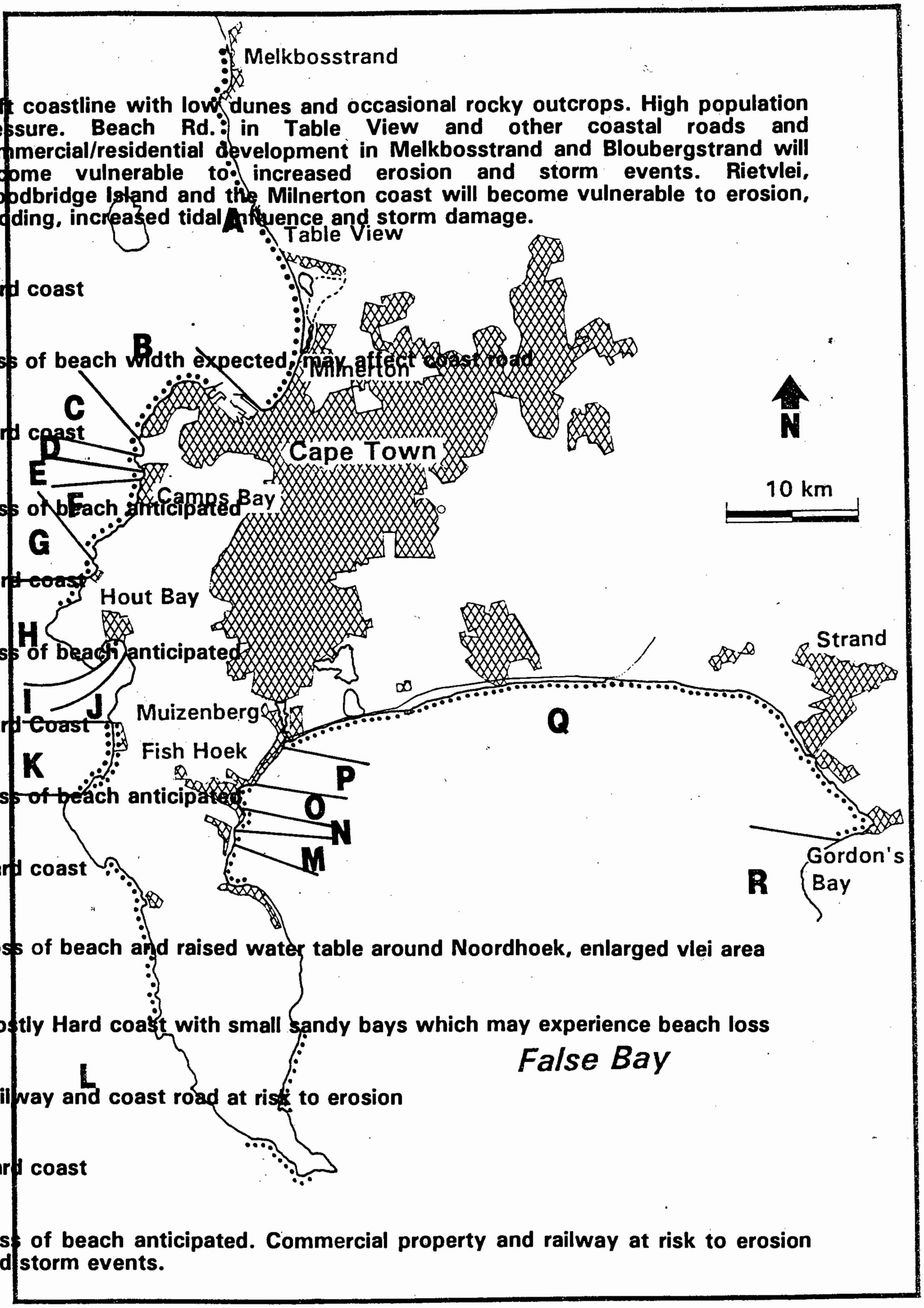
- Area E: Greater Cape Town. Melkbosstrand to Gordon's Bay.
- Area H: South Cape coast. Mossel Bay to Nature's Valley.
- Area K: Port Elizabeth.
- Area O: Natal south coast and Greater Durban. Southbroom to Ballitoville.

It is not entirely clear from the geological/morphological background why these regions should stand out as being particularly sensitive. They all have different physical factors which make up their vulnerability but their common factor in terms of societal impacts is their high population densities. Demand for land and other population pressures has forced development to take place in areas which are not entirely suitable for that use and as a result, changes in boundaries once thought of as fixed (i.e. the coastal boundary) reduce the suitability of that developed land even further. In addition, conflict arises between the desire to protect that development from the encroaching sea and need to allow the natural profile/shoreline migration to take place. Protection of the development may in certain circumstances enhance that development's vulnerability. The Natal south coast provides a prime example of this population pressure Vs. natural response conflict. In terms of its physical factors, the Natal south coast ranked as having a fairly low overall risk. However, the product of a low risk rating and a high population pressure is a higher risk area (in terms of societal impacts, irrespective of the vulnerability of rail-links, beaches and facilities which add to the desirability of living in that area).

The detail of the case studies has shown the impacts to be extremely site specific and within these four regions the level of vulnerability is not uniform. For example the Melkbosstrand to Gordon's Bay regions contains a variety of coastal landforms ranging from low lying sandy wetlands such as Rietvlei and the Diep river system to the 200 m high granite and sandstone cliffs of the Peninsula. A clarification of the potentially vulnerable areas within these sensitive regions is therefore necessary. Fig. 48 and Fig. 49 provide such clarifications for the Cape Town and southern Cape coasts. The

Port Elizabeth area is sufficiently defined and although it contains a range of environments, e.g. inlets to sandy bays to rocky and armoured foreshore, development has taken place close enough to the waterline to be at risk, even on the hard shore. This area has been identified by the regional : national scale comparisons as high risk and requires a detailed case study. Likewise almost the whole of the southern Natal section is vulnerable, save for a few rocky sections like The Bluff, as any change in beach character let alone any major shoreline change will be of significance to the considerable local population and tourist economy.

Clearly areas of high population density (i.e. coastal cities) are at highest risk due to the lack of land availability and development pressure on the shoreline. Risks range from a maximum loss of developments and infrastructure to a minimum change in recreational character of the resort beaches. All major coastal cities and towns should therefore undergo detailed impact assessment studies to identify vulnerable sites as a first step in managing the impacts. In addition, all future development in recognised sensitive areas (e.g. inlets, inlet mouths, foredunes) should be controlled and consideration of the impacts of sea level rise should be a prerequisite for new developments. Table 13 of Chapter 5 provides a list of likely sensitive rivers. This list is probably not exhaustive and is intended for use as a guideline only. However some idea of the size of the problem can be gained if one considers that of the Cape's fifty-three main rivers, 77% have soft or erodible mouths, 71% of these are backed by vleis and lagoons which will produce a disproportionate sea level rise : flooded area response. Some 62% of these are moderately to heavily developed. This percentage can only be expected to grow.



A
Soft coastline with low dunes and occasional rocky outcrops. High population pressure. Beach Rd. in Table View and other coastal roads and commercial/residential development in Melkbosstrand and Bloubergstrand will become vulnerable to increased erosion and storm events. Rietvlei, Woodbridge Island and the Milnerton coast will become vulnerable to erosion, flooding, increased tidal influence and storm damage.

B
Hard coast

C
Loss of beach width expected, may affect coast road

D
Hard coast

E
Loss of beach anticipated

F
Hard coast

G
Loss of beach anticipated

H
Hard Coast

I
Loss of beach anticipated

J
Hard coast

K
Loss of beach and raised water table around Noordhoek, enlarged vlei area

L
Mostly Hard coast with small sandy bays which may experience beach loss

M
Railway and coast road at risk to erosion

N
Hard coast

O
Loss of beach anticipated. Commercial property and railway at risk to erosion and storm events.

P
Hard coast with railway at risk from storm wave washover

FIGURE 43. Detail of vulnerability to sea-level rise for the Cape Town area.

Q
Coastal erosion risk to whole section especially Baden Powell Drive. Zandvlei and Marina da Gama at risk from flooding, increased tidal influence and damage from even small storms. Rocky outcrops towards east will tend to reduce erosion.

R

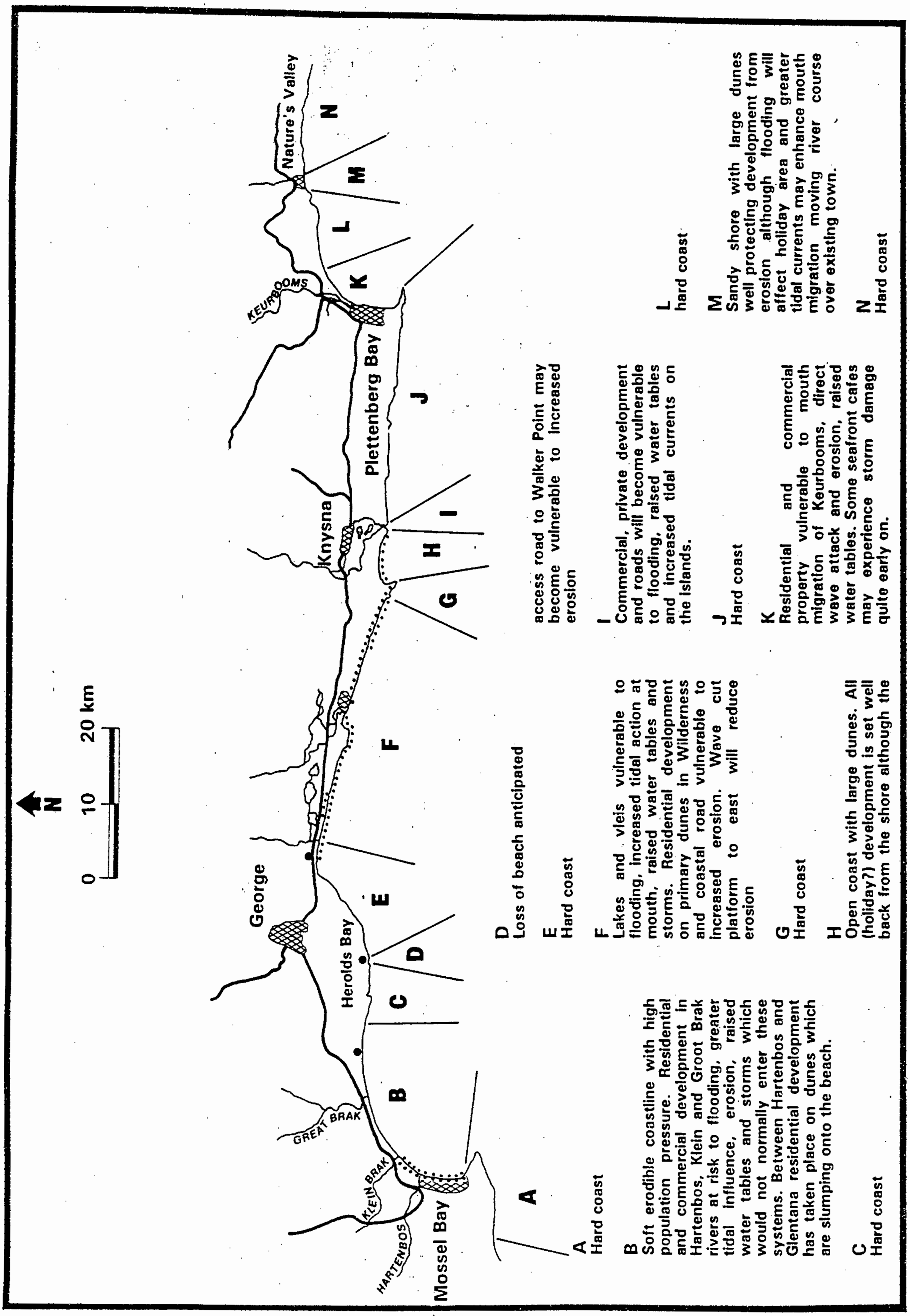


FIGURE 49. Detail of vulnerability to sea level rise for the southern Cape coast.

6.6 Management Options

After considering the impacts of sea level rise on the coast and where the relative impacts are going to be felt, the question arises - "what can be done in terms of coastal management to ameliorate the impacts in South Africa?" A recent poll of people in key planning positions in the Cape Town Metropolitan area (Sowman et al. 1990) recognized a certain knowledge of some of the consequences of global warming and sea level rise and indicated a need for central government to play a coordinating role in initiating a response to rising sea levels. The problems associated with planning for sea level rise have been addressed (Hughes and Brundrit 1991b) and a summary of the findings is presented:

At present there are a number of impediments to considering sea level rise in design and planning criteria (Gerstle 1989). The first is a lack of resolution of the present global climate models to make accurate predictions on a local scale to narrow down the range of future sea level rise. (This obstacle is rapidly being overcome). The second in the light of uncertainty of the impacts is the cost of over-designing for these impacts. The third relates to the community perception of the problem in that as the problem is not currently visible, it is difficult to conceptualize an accelerating range of deleterious impacts. In traditional areas of engineering there tends to be a high dependence on historical methods and a reluctance by professionals to recognise the risk. The fourth area of difficulty is a lack of experience of dealing with conceptual problems. "Politicians are constantly pressed to deal with immediate concerns. Planning for eventualities well outside their parliamentary term would be described in 'Yes Minister' parlance as a 'courageous approach' (Gestle 1989)." In view of the "New South Africa" and the likely reshuffling ahead, this last area of difficulty is probably the most serious of all.

When considering what action may be taken, there are four main avenues which may be followed and a number of possible methods within each course of achieving each aim:

1. Do nothing and see what happens. If sea level rise predictions are correct then this option may become very expensive when the problem is realised at a late stage in its development.

2. Restrict development to well behind areas of potential risk and front the development with a series of natural undeveloped buffer zones. This approach may be beneficial from an environmental point of view but could unnecessarily sterilize large tracts of valuable land.

3. Planned retreat. As the sea level rises allow the development to retreat landward in an organised fashion possibly allowing free market policy to dictate the time of migration. This would involve some complex legislation to provide for the assurance of such issues as the right to protection or non-protection of certain shores, forced purchases of properties and lease options.

4. Defend the development with either hard options such as walls or dykes or by soft options such as beach nourishment programs. After a certain period the latter option may become prohibitively expensive.

The IPCC in their Formulation of Response Strategies report (1990b) broadly categorises these responses into those of; Retreat, Accommodate and Protect. Retreat involves no effort to protect the land from the sea. The coastal zone is abandoned and ecosystems shift landward. This choice can be motivated by excessive economic or environmental impacts of protection. Accommodation implies that people continue to use the land at risk but do not attempt to prevent the land from being flooded. This option involves the erection of emergency flood shelters, elevating buildings on piles, converting agriculture to fish farming, or growing flood or salt tolerant crops. Protection involves hard structures such as sea walls and dykes, as well as soft solutions such as dunes and vegetation, to protect the land from the sea so that existing land uses may continue. This IPCC reference and the RAP response terminology is likely to be used in the future and consequently is the preferred work here. "The appropriate mechanism for implemention depends on the particular response. Assuming that land for settlement is available, retreat can be implemented through anticipatory land use regulations, building codes or economic incentives. Accommodation may evolve without any government action, but could be assisted by strengthening flood preparation and flood insurance programmes. Protection can be implemented by the authorities currently responsible for water resources and coastal protection (IPCC 1991b)."

Each course of action is correct in its appropriate location. The problem comes in deciding what is the appropriate location and at what cost. A comparison of international approaches to the problems of sea level rise may therefore be useful. The Australian scenario is stressed in the following examples because of the similarity between the two countries' wind, wave and general climatology, coastal morphology and land availability.

6.6:1 International approach to sea level rise

Australia is a highly urbanised nation, with over 80 % of the population concentrated on the coastal fringe. All state capitals are on coastal plains and the majority of the population is vulnerable to any sea level change (Gerstle 1991). It is hardly surprising to learn therefore that the consequences of sea level rise have been taken seriously for some time. For example South Australia developed sea level rise strategies as early as 1985 (Gerstle 1991). The South Australian policy encourages developments to be "protected from, or be able to be protected from" an identified sea level rise. In this area the predicted rate of relative sea level rise is 0.4 m over 50 years. Although no specific greenhouse induced sea level change is included in the calculations, the general policy of incorporating flexibility in the design of structures allows modification to protect developments when this becomes necessary (Gerstle 1991).

The Queensland government has developed a more comprehensive approach for many facets of the greenhouse effect but has adopted a similar philosophy to the South Australia model (Gerstle 1991). The Queensland document states: "To avoid circumstances where some local authorities require consideration of sea level rise in design of development on the coast, and others ignore it, and to protect local authorities and approval agencies from legal action from landowners who consider themselves adversely affected, it is proposed all agencies with the responsibility for approving developments likely to be affected by sea level rise to adopt the following policy:-

1) design of developments is to be such that a sea level rise of 0.8 m by the year 2030 can be accommodated, either in the original construction or by later modification; and
2) the siting of coastal developments to be such that the expected coastal erosion due to sea level rise of 0.8 m by the year 2030 may be accommodated."
The essential elements of this policy are that developments are able to be modified to Accommodate sea level rise when necessary, and that approval authorities are provided a common standard and therefore avoid legal liability for approval of developments that may become at risk in the future (Gerstle 1991).

The Victoria Government published a draft strategy which included a number of more specific recommendations. Areas of "high vulnerability and high consequence" are to be identified "to facilitate the preparation of management plans." Further definition is provided to "Prohibit development in areas at risk, that is, those which will be inundated by an extreme tide or a combination of rainfall and tides, which has a probability of occurrence of 1 % in any year (average return period 100 years. Median values for a sea level rise of 30 cm for 2040 will be applied to the 1 % annual tide to determine the appropriate building design levels. The figure will be reviewed as new information becomes available" (Gerstle 1991). Although this is a more proscriptive approach, it incorporates flexibility as better information becomes available.

The New South Wales Government is presently formulating a coastal management manual which introduces a Coastal Hazards Policy. The primary aim of this policy is "to reduce the impact of coastal processes on owners and occupiers of the coastal area and to reduce public and private losses resulting from such processes" without unnecessarily sterilizing land (Hibbert and Tainsh 1990).

A number of strategies (Hibbert and Tainsh 1990) have been adopted to implement the policy with the basic premise that the day to day development and planning decision lies with local government. The key elements of the strategies are:

- Introduction of financial assistance and continuation of technical assistance by the State to Local Government for the studies necessary for development of management strategies and for the implementation of those strategies.

- Continuation of financial assistance for projects to improve the recreational amenity of the State's beaches.

- Preparation of a Manual containing guidelines and principles to assist Local Government in dealing with development proposals, and in preparing and implementing plans for Management.

- Legislation to protect public authorities and their staff against claims for damages providing they act in accordance with the Manual.

The Management system places emphasis on "merit based balanced planning and development decisions" and has elements as shown in Fig. 50.

The Committee comprises senior Council (Local Government) staff and elected technical members and community group leaders. The Coastal Process/Hazard Definitive Study is a specialist technical investigation which ultimately identifies the coastal hazard threatening a particular length of coastline. The Coastal Management Study considers all feasible management options. The Coastal Management Plan involves the formal adoption of a defined coastline management strategy and the Plan Implementation uses various approaches to implement the various elements of the said plan. With reference to climatic change the policy stages "in the light of present uncertainty (of climatic change), an adoptive approach towards planning and design in the coastal zone is necessary. This approach should be sufficiently flexible or 'robust' to be able to cater for a range of possible outcomes, i.e. Management decision should be subjected to a 'hazard risk sensitivity analysis'" (Hibbert and Tainsh 1990). This effectively forces the local planners to acknowledge their professional responsibility towards sea level rise without necessarily forcing design changes at this stage.

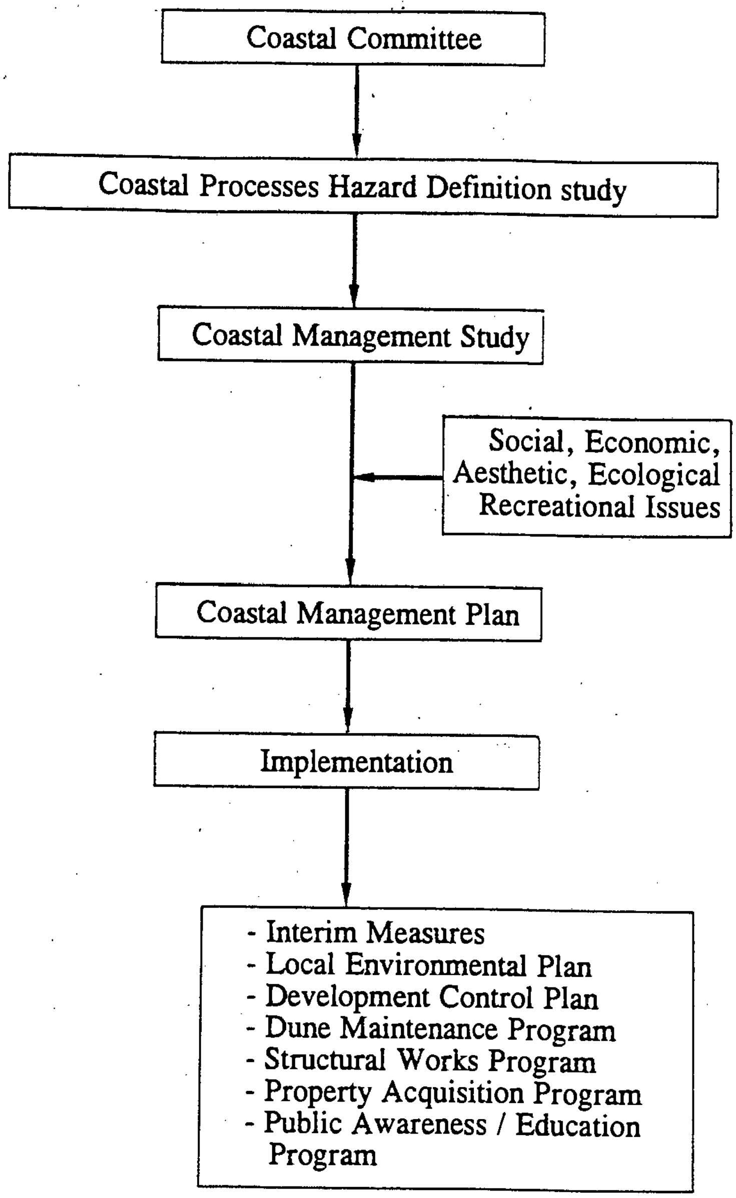


FIGURE 50. Elements of the New South Wales Coastal Management System (after Hibbert and Tainsh 1990).

The Western Australian State Government has evolved a unique and non-statutory approach to coastal management which meets its own needs. "The system is based on a policy of cooperation between State departments and local government authorities. The State has, over many years, retained public ownership of the majority of coastal land by a policy of non-alienating State land and by resuming foreshore reserves when freehold land is subdivided. This effectively provides for a buffer zone between ocean and privately owned land resulting in minimal storm damage in the private sector. In 1983 the Western Australian State

Government made a conscious decision to continue with its non-statutory approach and it is likely that because of its lengthy coastline, small population and tax base, this approach will be continued despite rising sea levels" (O'Brien 1988).

Coastal Zone Management in the United States is accomplished through a cooperative federal and state program to manage and protect coastal resources. It is predominantly a state responsibility subject to very general national guidelines but implementation is often delegated to local governments with the implicit assumptions that the local authorities accept the state's role as their partner in regulating land use in the coastal zone (Klarin and Hershman 1990). This requires collaboration with federal agencies and federal laws give powers to such agencies to address coastal zone hazards, for example:

The Clean Water Act requires the Environmental Protection Agency (EPA) to protect virtually all aspects of the nation's water resources. One of EPA's areas of concern is the protection of wetlands and their vulnerability to sea level rise and development. The EPA has been instrumental in developing a technical information base and a network of scientific and policy experts. It provides a national focus for the sea level rise issue and serves as a primary educational resource for many initial efforts of state coastal zone management programs (Klarin and Hershman 1990).

The National Flood Insurance Program administered by the Federal Emergency Management Agency provides federally subsidized insurance for damage to structures by storms in certain qualifying communities. In the past it has been criticised as providing incentives for development and rebuilding in the coastal flood zone contrary to the spirit of the program. However legislative changes now provides incentive to remove damaged structures or relocate threatened structures in hazardous zones (Klarin and Hershman 1990).

The Coastal Barriers Resource Act creates a national system of coastal barrier areas within which the federal government prohibits federal subsidies for infrastructure and hazard insurance (Klarin and Hershman 1990). This effectively limits massive new infrastructural development in

barrier areas such as wetlands and dunes; areas which may otherwise be considered prime real estate.
The U.S. Army Corps of Engineers has the longest and most direct involvement in coastal development through laws which authorise the Corps to regulate development affecting the nation's navigable waters. No formal policy has been adopted but historic sea level changes have always been factored into their engineering designs (Klarin and Hershman 1990).

Sixty-five percent of the U.S. population or 102 M people live within 50 miles of the coast (Klarin and Hershman 1990) and significant coastal erosion affects approximately a quarter of the U.S. coastline. Fifteen states or territories use a system of setbacks or building restrictions to counter this erosion (Houlahan 1989). Of the fifteen, four use fixed setback policies where the setback distance is determined <u>prior</u> to permit applications. The fixed setback is usually referred to a stationary reference point such as a monument or road and is therefore easy to apply on maps and structural plans. It is, however, unresponsive to shoreline dynamics. The remaining eleven states and territories use a principle of floating setback where the setback distance is determined <u>when</u> a permit is requested and is based on a multiple of average annual long-term recession rates. The multiplier is usually of the order of 30 to 100 years recession. In addition to the floating setback some states divide the coastline into high and low hazard areas, requiring a greater or lesser degree of setback, and also considers the structure size in determining the setback distance. Within the operation of management procedure these states endeavour to make the setback program understandable to the general public. With this flexible setback program a planned retreat in the face of rising sea levels could be easily accommodated.

Studies using relative sea level rise in the Mississippi River delta as an analog for eustatic sea level rise in wetlands (Day and Templet 1989) emphasize two important factors:

1. There may often be a lag of decades before a response of the natural system to sea level rise becomes evident.

2. Changes may be slow at first but will accelerate.

This study recommends that "coastal wetlands can be managed to survive rising sea levels but that only comprehensive, integrated, long term planning can effectively deal with the problem of sea level rise."

Keillor (1990) in his paper "Planning for a Wider Range of Water Levels along the Great Lakes and Ocean Coasts," describes institutional responses to record high water levels in the Great Lakes during 1985 and 1986. He suggests that this situation exemplifies a dress rehearsal for future sea level rise. In this case, education of coastal dwellers was one of the key factors which helped reduced the level of impact. The Wisconsin Sea Grant Institute held meetings in coastal cities with groups of local officials and coastal property owners and organised workshops for coastal engineers and realtors. Material was prepared to teach coastal investors how to make their own evaluation of the risk of flooding and erosion to coastal property, This extended beyond the prospective property owner to bankers and insurers. A manual and workbook were prepared and people were trained. Within a year 12 of the 77 students had trained others and nearly half had used the manual to exercise some professional influence on property purchasing decisions. This case study further stresses the need for a clarified institutional response to changing water levels in order to minimize impacts.

After considering the approaches of other governments and the impending problems it is clear that "by acceptance in principle, and adopting a policy that includes conservative (low) short term estimates of change, a 'reasonable approach' to the issue can be achieved. As more conclusive evidence becomes available, it is a matter of improving the 'numbers' rather than belatedly establishing a policy" (Gerstle 1989). In all cases, public awareness and if possible education, is beneficial to the smooth operation of any coastal management plan. Management for future sea levels therefore, will certainly require some considerable education effort.

6.7 What can be done in South Africa?

As a result of changes to the earth's atmospheric assemblage, changes in mean global temperature and global climate have been predicted and the term "Greenhouse Effect" has been coined to describe the processes involved. One of the results of the Greenhouse Effect is a predicted rise in sea level, possibly as much as 1 metre over the next century; - i.e. a rate greater than previously experienced during any deglaciation period for which evidence is available. Global temperatures and sea level appear to be rising already and South African tide gauge records indicate that the sea level is rising around South Africa at a rate comparable to global estimates. It is likely therefore that this rate will continue to be comparable and the impacts of sea level rise and climatic change on the South African coastal environment are therefore of growing concern to coastal managers and planners. South Africa must take a proactive role in order to avoid detrimental effects of sea level rise which could have been avoided or managed by effective early planning decisions.

In reviewing the impacts of sea level rise the first observable impact will probably be an increase in storm damage along the coast. With rising sea level, smaller and therefore more frequently occurring storms will be capable of over-topping existing defences - formal or informal. Soft erodible coastlines will retreat, though not at a constant rate, and must be allowed "room" to retreat. Where there is no room and the profile has been fixed by a structure, the characteristics of the shore/beach will change and the very presence of the structure's protection will result in its own increased vulnerability. Inlets, estuaries, river mouths and tidal lagoons will become more tidal with resultant changes to channel and mouth characteristics and nearby shoreline. A greater flooded area will be formed and this may stress certain wetland habitats if development around these environments is not carefully managed. Some new lagoons/inlets may even be created where they previously did not exist. Associated with the sea level rise will be an rise in the groundwater table. Areas which were previously dry may become marshy or at least suffer from high water-tables, possibly with accompanying engineering problems. This may be particularly important for islands in estuaries. Note that the coastal water-table will rise everywhere along the coast, even in urban areas, unless suitable aquifer management is carried out. Likewise increased saline intrusion into the coastal aquifers must be managed and may also be necessary in some rivers.

Overall, erosional impacts will be more important along the Natal coast due to the narrow coastal plain and presence of development on the primary dunes and river spits. Along the Cape coast the impacts will be more inundative in character, affecting the region's more highly developed inlets and estuaries. In the final analysis, population pressure is the critical factor deciding a location's vulnerability with those inlets and coastal wetlands, their channels, banks and mouths, low lying shorelines and primary dunes providing the most sensitive environments.

Additional research is required and three study areas are identifiable. The first considers baseline observations to improve the estimates and verify the occurrence of rapidly rising sea levels. The second is directed towards observations of those symptoms of sea level rise, in order to support the baseline observations. The third considers precautions and studies to improve the response in the event of rapid sea level rise.

1. Tide gauges provide the baseline observations of sea levels and unfortunately South Africa does not have a very good historical record. Every effort must be made to ensure the capture of quality data from new and existing gauges and the status of these locations should be upgraded to expedite accurate data capture. In addition to the measurement of trends, the recording of extreme sea levels must be seen to be of great importance. Only through the study of actual storm levels at a given location can future extreme levels be modelled and hopefully one day predicted for that location. More tide gauges should therefore be employed.
2. Increased coastal erosion is one of the most obvious symptoms of sea level rise. Regular aerial surveys of the whole coast must be flown on a long-term basis to monitor coastline changes. Programs should be implemented so that regular surveys of beach and nearshore profiles are carried out monitoring changes in rates of longshore sediment transport. Proxies such as rates of beach nourishment (e.g. Durban) and rates of maintenance dredging in channels could be used and the accurate record keeping of quantities moved should be encouraged. Rates of sediment bypassing across inlets should also be monitored.

Other symptoms such as increases in storm damage should be investigated and storm damage reporting, complete with estimates of water levels and erosion rates, could become a useful exercise.

3. A list of precautions and valuable studies to undertake would be unsuitable in this context and probably incomplete. However a few suggestions may be made which may help improve this country's response to rising sea levels;-

   A more detailed vulnerability assessment for South Africa is essential and should be instigated. All coastal population centres must undergo some form of Potential Impact Assessment, even at a low intensity, in order to identify likely problematical areas. Tidal inlets (sensitive environments) should be the subject of a number of detailed studies involving water level monitoring and response to extreme levels. Those towns with inadequate surface freshwater supplies and a (partial) reliance on underground water should undertake detailed aquifer studies and co-ordinate their long-term mining. Research into coastal management and protection techniques should be promoted and access to beaches should be controlled in order to protect and encourage dune vegetation.

A formal approach to the planning and management procedures for future climate change and sea level rise in South Africa must be adopted and it is suggested that legislation be implemented at two levels. First, the overall problem of potential risk from the changing global climate and associated sea level rise should acknowledged at a state governmental level. In doing so the government would ensure that planners and coastal engineers are forced to recognise their professional responsibility in the light of these impending environmental changes. The second level of management should be more specific and aimed at local management decisions, requiring any proposed management plan in an area identified as potentially sensitive to sea level rise, to be subject to a sea level rise "hazard test". The system should form an integral part of the Integrated Environmental Management philosophy (IEM 1989) and Coastal Zone Management policy (Parts 1 & 2, 1989) and should not be regarded as a separate piece of legislation.

Incorporation of the application of the Small Scale Coastal Vulnerability Index (Hughes and Brundrit 1991a) to sea level rise within the Coastal Zone Management Part 1 (Environmental Guidelines for Regional Planning)

Policy No.2 could form a practical step in the planning. In its guidelines, Policy 2 calls for "an inventory of coastal landforms, visually appealing landscape features and biological resources." The addition of an assessment of general vulnerability to sea level rise (CVI) could improve this inventory by including potentially vulnerable locations. This could be based on an overlap of high population/development pressure with those recognised "sensitive environment types" around the coast.

Within Part 2 of this policy - "Guidelines for the Use of Coastal Landforms" - could come the sea level rise "hazard test" as applied to the management procedures of an area identified by the inventory and CVI of policy No.2. Within these procedures the strategies of non-protection, planned retreat, hard and soft engineering controls may be applied to any new or existing development based on the results of detailed Potential Impact Assessments or case studies. Finally, as an aid to judicious decision making, legislation to protect public authorities and their staff (similar to the NSW case) against claims for damages providing they act in accordance with these procedures should also be considered.

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APPENDIX 1

RISK RATINGS FOR THE SOUTH CAPE COAST

HAZARD RATING FOR COASTAL EROSION

	Private Houses	Comm. Props.	Dev.Res. Props.	Main Road	Minor Rd /Car Park	Agri. Land	Road Bridge	Rail Bridge	Railway
Natures Valley									
Keurboomstrand	1								
Plettenburg Bay N/ Keurbooms River Mouth			2						
Plettenburg Bay S.	1	2			2				
Noetzie									
Knysna									
Brenton on Sea									
Walker Point/Buffels Bay	1		1	2					
Sedgefield									
Kleinkrantz	1								
Flat Rock Beach		2							
Wilderness	2			1	1				
Victoria Bay									
Herolds Bay	1				1				
Glentana & Outeniqua (S)	2		2		1				
Bothastrand	2								
Groot Brak River									
Tergriet & Reebok	1				1				
Klein Brak River	1								
Hartenboss	1	1	1		1				
Bay View	2		2		2				
Voorbaai									
Diastrand									
Mosselbay									
Danabaai	1								
Boggoms Baai	1		1						
Vleesbaai	1								
Gouritzmond									
Stilbaai	2				2				

	Private Houses	Comm. Props.	Dev.Res. Props.	Main Road	Minor Rd /Car Park	Agri. Land	Road Bridge	Rail Bridge	Railway
Jongensfontein									
Witsand, Port Beaufort, Breerivier Mouth									
TOTAL	21	5	9	3	10				

HAZARD RATING FOR FLOODING AND INUNDATION

	Private Houses	Comm. Props.	Dev.Res. Props.	Main Road	Minor Rd /Car Park	Agri. Land	Road Bridge	Rail Bridge	Railway
Natures Valley	2		2	2	2				
Keurboomstrand									
Plettenburg Bay N/ Keurbooms River Mouth	1	1	1		1	1			
Plettenburg Bay S.									
Noetzie									
Knysna	2	2		2	2				
Brenton on Sea									
Walker Point/Buffels Bay									
Sedgefield	2		2	1	2		1		
Kleinkrantz									
Flat Rock Beach									
Wilderness	2	1	2	1	1				1
Victoria Bay									
Herolds Bay									
Glentana & Outeniqua									
Bothastrand									
Groot Brak River	2	2	2	1	1	2	1	1	1
Tergriet & Reebok									
Klein BrakRiver	1								
Hartenboss									
BayView									
Voorbaai									
Diastrand									
Mossel Bay									
Danabaai									
Boggoms Baai									
Jleesbaai									
Gouritzmond									
Stilbaai	1	1	1	2	2				

	Private Houses	Comm. Props.	Dev.Res. Props.	Main Road	Minor Rd /Car Park	Agri. Land	Road Bridge	Rail Bridge	Railway
Jongersfontein									
Witsand, Port Beaufort, Breerivier Mouth									
TOTAL	13	7	10	9	11	3	2	1	2

HAZARD RATINGS VULNERABLE TO GROUNDWATER EFFECTS

	Private Houses	Comm. Props.	Dev.Res. Props.	Main Road	Minor Rd /Car Park	Agri. Land	Road Bridge	Rail Bridge	Railway
Natures Valley	2		2	2	2				
Keurboomstrand									
Plettenburg Bay N/ Keurbooms River Mouth	2	2	2		2	2			
Plettenberb Bay S.	2				1	1			
Noetzie									
Knysna	2	2	2	2	2	1	1	1	2
Brenton on Sea									
Walker Point/Buffels Bay									
Sedgefield	2	2	2	2	2	1			
Kleinkrantz									
Flat Rock Beach									
Wilderness	2	1	2		2		1	1	1
Victoria Bay									
Herolds Bay									
Glentana & Outenique									
Bothastrand									
Groot Brak River	2	2	2	1	2				2
Tergriet & Reebok									
Klein Brak River	1		1		1	1			
Hartenboss			2						
Bay View									
Voorbaai									
Diastrand									
Mossel Bay									
Danabaai									
Boggoms Baai									
Vleesbaai									
Gouritzmond						2			
Stilbaai	2	2	2	2	2	1			

	Private Houses	Comm. Props.	Dev.Res. Props.	Main Road	Minor Rd /Car Park	Agri. Land	Road Bridge	Rail Bridge	Railway
Jongersfontein									
Witsand, Port Beaufort, Breeriver Mouth									
TOTAL	17	11	17	9	16	9	2	2	5

HAZARD RATING TO EXTREME EVENTS

	Private Houses	Comm. Props.	Dev.Res. Props.	Main Road	Minor Rd /Car Park	Agri. Land	Road Bridge	Rail Bridge	Railway
Natures Valley	2		2	2	2				
Keurboomstrand	1								
Plettenberg Bay N/ Keurbooms River Mouth	2	2	2		1	1			
Plettenberg Bay S.	2	2	1	2	2		2		
Noetzie									
Knysna	2	2		2	2		2	2	2
Brenton on Sea									
Walker Point/Buffels Bay	1			2					
Sedgefield	2		2	2	2		2		
Kleinkrantz									
Flat Rock Beach									
Wilderness	2	1	2	1	2		2	2	1
Victoria Bay									
Herolds Bay	1								
Glentana & Outeniqua	1								
Bothastrand	1								
Groot Brak River	2	2		2	2		2	2	2
Tergriet & Reebok									
Klein Brak River	2		2	2	2	1	1	2	
Hartenboss		1	2		1		1	1	
Bay View	2								
Voorbaai									
Diastrand									2
Mossel Bay	1	1			1				
Danabaai									
Boggoms Baai									
Jleesbaai	1								
Gouritzmond	2		2		2	1			
Stilbaai	2	1	2	2	1		1		

	Private Houses	Comm. Props.	Dev.Res. Props.	Main Road	Minor Rd /Car Park	Agri. Land	Road Bridge	Rail Bridge	Railway
Jongersfontein	1								
Witsrand, Port Beaufort, Breerivier Mouth	1								
TOTAL	31	12	17	17	20	3	13	9	7

HAZARD RATING FROM GREATER TIDAL INFLUENCE IN RIVER MOUTHS

	Private Houses	Comm. Props.	Dev.Res. Props.	Main Road	Minor Rd /Car Park	Agri. Land	Road Bridge	Rail Bridge	Railway
Natures Valley	2			2	2				
Keurboomstrand									
Plettenburg Bay N/ Keurbooms River Mouth	2	2	2		1	1			
Plettenburg Bay S.	1			1	1		1	1	
Noetzie									
Knysna	1	1		1	1		1	1	
Brenton on Sea									
Walker Point/Buffels Bay			1						
Sedgefield	1				1				
Kleinkrantz									
Flat Rock Beach									
Wilderness	2	1	2	2	1		2	2	
Victoria Bay									
Herolds Bay									
Glentana & Outeniqua									
Bothastrand									
Groot Brak River	2	1			2	1	2	2	
Tergriet & Reebok									
Klein Brak River	1				1		1	2	
Hartenboss	1	1				1	1	1	
Bay View									
Voorbaai									
Diastrand									
Boggoms Baai									
Vleesbaai									
Gouritzmond	1					1			
Stilbaai	1	1	1	2	1		1		

	Private Houses	Comm. Props.	Dev.Res. Props.	Main Road	Minor Rd /Car Park	Agri. Land	Road Bridge	Rail Bridge	Railway
Jongersfontein Witsrand, Port Beauford/ Breerivier Mouth									
TOTAL	15	7	6	8	11	4	9	9	

HAZARD RATING SOUTH CAPE COAST

HAZARD	SUM	SUM/n (unit vuln.)	REGIONAL UNIT VULN. (scaled by minimum)
Extreme events	131	5.03	2.72
Raised groundwater	88	3.38	1.82
Greater tidal infl.	69	2.65	1.43
Flooding and innund.	58	2.23	1.21
Increased erosion	48	1.85	1

n = number of vulnerable locations (26)

INFRASTRUCTURE RATING SOUTH CAPE COAST

INFRASTRUCTURE	SUM	SUM/n (unit vuln.)	REGIONAL UNIT VULN. (scaled by minimum)
Private housing	97	3.73	7.01
Minor road	68	2.61	4.92
Developing res. land	59	2.27	4.28
Main road	46	1.77	3.34
Commercial property	42	1.62	3.06
Road bridge	26	1.00	1.89
Rail bridge	21	0.81	1.53
Agricultural land	19	0.73	1.38
Railway	14	0.53	1

APPENDIX 2

RISK RATINGS FOR THE NATAL SOUTH COAST

HAZARD RATING FOR COASTAL EROSION

	Private Houses	Comm. Props.	Dev.Res. Props.	Main Road	Minor Rd /Car Park	Agri. Land	Road Bridge	Rail Bridge	Railway
Durban Bluff, Sloane Road	1								
Mission Beach		1			1				
Anstey's Beach		2			2				
Brighton Beach		2			2				
Brighton Beach to Mlazi Canal									
Mlazi Canal									
Isipingo Beach									
Tiger Rocks(N)		1			1				
Pipeline Beach		1			1				
Umbogintwini (S)									
Amanzintoti North									
Amanzintoti Nyoni Rocks to Lagoon									
Amanzintoti Lagoon									
Amanzintoti to Doonside Beach									
Doonside Beach									
Doonside Beach S.									
Warmer Beach									
Winklespruit Beach									
Illovo Beach									
Karridene									
Umgababa		2							1
Umgababa Riv. Mouth								1	1
Sunlight Beach									
Ilfracombe N			2						
Umkomas					2				
Widenham									
Mahlangwa Riv. Mouth									
	Private	Comm.	Dev.Res.	Main	Minor Rd	Agri.	Road	Rail	Railway

	Private Houses	Comm. Props.	Dev.Res. Props.	Main Road	Minor Rd /Car Park	Agri. Land	Road Bridge	Rail Bridge	Railway
Clansthal	2		2		2				
Green Point Manba									
Alley to Black Rks									1
Freeland Park		1							
Mpambagani Riv. to									
Scottburgh South		2			1				
Scottburgh South									
Park Rynie									
Mzinayi Riv. Mouth									
Kelso, Station Bay									
Kelso Pennington									
Beach									2
Pennington									
Sezela		1							
Ifafa Beach									
Elysium									
Mtwalane									
Hibberdene		1			1				
Hibberden,									
Pleasant Valley		2			2				
Woodgrange									
Umzumbe				2					2
Umzumbe									
Kellerman Rock									
Banana Beach N									2
Banana Beach to									
Bendigo Sunwich									
Point									
Bendingo									
Sunwich Port									
South Point									
Sea Park									
Umtentwini									
Port Shepstone				2					2

	Houses	Props.	Props.	Road	/Car Park	Land	Bridge	Bridge	
Port Shepstone, Station Bay					2				
Port Shepstone, Lucky Dip Bay		1			1				
Port Shepstone S									
Mbango									
Oslo Beach									
Shelley Beach North	1								
Shelly Beach		1				1			
St Michaels on Sea									
St Michaels on Sea, Orange Rocks to Uvongo									
Uvongo Beach									
Uvongo Beach to Manaba Beach									
Margate		2							
Margate S									
Ramsgate N									
Ramsgate, Bilanhlold Riv.									
Ramsgate, Mvutshinti River									
Ramsgate S									
Southboom									
Marina Beach, Kent Bay									
Marina Beach S									
Empanjati									
Trafalgar									
Palm Beach									
Munster									
Portobella									
Port Edward									
TOTAL	4	20	4	4	18	1		1	11

HAZARD RATING FOR FLOODING AND INUNDATION

	Private Houses	Comm. Props.	Dev.Res. Props.	Main Road	Minor Rd /Car Park	Agri. Land	Road Bridge	Rail Bridge	Railway
Durban Bluff, Sloane Road									
Mission Beach									
Anstey's Beach									
Brighton Beach									
Brighton Beach to Mlazi Canal									
Mlazi Canal									
Isipingo Beach									
Tiger Rocks(N)									
Pipeline Beach									
Umbogintwini (S)									
Amanzintoti North									
Amanzintoti Nyoni Rocks to Lagoon									
Amanzintoti Lagoon									
Amanzintoti to Doonside Beach									
Doonside Beach									
Doonside Beach S.									
Warmer Beach									
Winklespruit Beach									
Illovo Beach									
Karridene									
Umgababa									
Umgababa Riv. Mouth									
Sunlight Beach									
Ilfracombe N									
Umkomas									
Widenham									
Mahlangwa Riv. Mouth									

	Private Houses	Comm. Props.	Dev.Res. Props.	Main Road	Minor Rd /Car Park	Agri. Land	Road Bridge	Rail Bridge	Railway
Clansthal									
Green Point Manba Alley to Black Rks									
Freeland Park									
Mpambagani Riv. to Scottburgh South									
Scottburgh South									
Park Rynie									
Mzinayi Riv. Mouth									
Kelso, Station Bay									
Kelso Pennington Beach									
Pennington									
Sezela		1							
Ifafa Beach									
Elysium									
Mtwalane									
Hibberdene									
Hibberden, Pleasant Valley									
Woodgrange									
Umzumbe									
Umzumbe									
Kellerman Rock									
Banana Beach N									
Banana Beach to Bendigo Sunwich Point									
Bendingo Sunwich Port									
South Point									
Sea Park									
Umtentwini									
Port Shepstone									

	Private Houses	Comm. Props.	Dev.Res. Props.	Main Road	Minor Rd /Car Park	Agri. Land	Road Bridge	Rail Bridge	Railway
Port Shepstone, Station Bay									
Port Shepstone, Lucky Dip Bay									
Port Shepstone S									
Mbango									
Oslo Beach									
Shelley Beach North									
Shelly Beach									
St Michaels on Sea									
St Michaels on Sea, Orange Rocks to Uvongo									
Uvongo Beach									
Uvongo Beach to Manaba Beach									
Margate									
Margate S									
Ramsgate N									
Ramsgate, Bilanhlold Riv.									
Ramsgate, Mvutshinti River									
Ramsgate S									
Southboom									
Marina Beach, Kent Bay									
Marina Beach S									
Empanjati									
Trafalgar									
Palm Beach									
Munster									
Portobella									
Port Edward									
TOTAL		1							

HAZARD RATING FOR ELEVATED GROUNDWATER TABLE

	Private Houses	Comm. Props.	Dev.Res. Props.	Main Road	Minor Rd /Car Park	Agri. Land	Road Bridge	Rail Bridge	Railway
Durban Bluff, Sloane Road									
Mission Beach									
Anstey's Beach									
Brighton Beach									
Brighton Beach to Mlazi Canal									
Mlazi Canal									
Isipingo Beach									
Tiger Rocks(N)									
Pipeline Beach									
Umbogintwini (S)									
Amanzintoti North									
Amanzintoti Nyoni Rocks to Lagoon									
Amanzintoti Lagoon									
Amanzintoti to Doonside Beach									
Doonside Beach									
Doonside Beach S.									
Warmer Beach									
Winklespruit Beach									
Illovo Beach									
Karridene									
Umgababa									
Umgagaba Riv. Mouth									
Sunlight Beach									
Ilfracombe N									
Umkomas									
Widenham									
Mahlangwa Riv. Mouth									

	Private Houses	Comm. Props.	Dev.Res. Props.	Main Road	Minor Rd /Car Park	Agri. Land	Road Bridge	Rail Bridge	Railway
Clansthal									
Green Point Manba Alley to Black Rks									
Freeland Park									
Mpambagani Riv. to Scottburgh South									
Scottburgh South									
Park Rynie									
Mzinayi Riv. Mouth									
Kelso, Station Bay									
Kelso Pennington Beach									
Pennington									
Sezela									
Ifafa Beach									
Elysium									
Mtwalane									
Hibberdene									
Hibberden, Pleasant Valley									
Woodgrange									
Umzumbe									
Umzumbe									
Kellerman Rock									
Banana Beach N									
Banana Beach to									
Bendigo Sunwich Point									
Bendingo Sunwich Port									
South Point									
Sea Park									
Umtentwini									
Port Shepstone									

	Private Houses	Comm. Props.	Dev.Res. Props.	Main Road	Minor Rd /Car Park	Agri. Land	Road Bridge	Rail Bridge	Railway
Port Shepstone, Station Bay									
Port Shepstone, Lucky Dip Bay									
Port Shepstone S									
Mbango									
Oslo Beach									
Shelley Beach North									
Shelly Beach									
St Michaels on Sea									
St Michaels on Sea, Orange Rocks to Uvongo									
Uvongo Beach									
Uvongo Beach to Manaba Beach									
Margate	1	1							
Margate S									
Ramsgate N									
Ramsgate, Bilanhlold Riv.									
Ramsgate, Mvutshinti River									
Ramsgate S									
Southboom									
Marina Beach, Kent Bay									
Marina Beach S									
Empanjati									
Trafalgar									
Palm Beach									
Munster									
Portobella									
Port Edward									
TOTAL	1	1							

HAZARD RATING FOR EXTREME EVENTS

	Private Houses	Comm. Props.	Dev.Res. Props.	Main Road	Minor Rd /Car Park	Agri. Land	Road Bridge	Rail Bridge	Railway
Durban Bluff, Sloane Road	2								
Mission Beach		2			2				
Anstey's Beach		2			2				
Brighton Beach		2			2				
Brighton Beach to Mlazi Canal									
Mlazi Canal		1			1				
Isipingo Beach	2	2			2		1		
Tiger Rocks(N)		1			1				
Pipeline Beach		2			1				
Umbogintwini (S)									
Amanzintoti North									
Amanzintoti Nyoni Rocks to Lagoon									
Amanzintoti Lagoon		1							
Amanzintoti to Doonside Beach									
Doonside Beach									
Doonside Beach S.					1				
Warmer Beach		1							
Winklespruit Beach									
Illovo Beach								1	
Karridene								1	
Umgababa		2							2
Umgababa Riv. Mouth								1	1
Sunlight Beach		1							
Ilfracombe N				2					
Umkomas					2		1	1	
Widenham									1
Mahlangwa Riv. Mout								1	1

	Private Houses	Comm. Props.	Dev.Res. Props.	Main Road	Minor Rd /Car Park	Agri. Land	Road Bridge	Rail Bridge	Railway
Clansthal	2		2		2				
Green Point Manba Alley to Black Rks									1
Freeland Park									
Mpambagani Riv. to Scottburgh South									
Scottburgh South		2			1				
Park Rynie		1			1				
Mzinayi Riv. Mouth							1	1	
Kelso, Station Bay									
Kelso Pennington Beach									2
Pennington									
Sezela		2							2
Ifafa Beach									
Elysium							1	1	
Mtwalane									
Hibberdene		1			1				
Hibberden, Pleasant Valley		2			2				
Woodgrange									
Umzumbe									
Umzumbe				2					2
Kellerman Rock									
Banana Beach N									2
Banana Beach to Bendigo Sunwich Point									
Bendingo Sunwich Port					1				
South Point	1								
Sea Park	1								
Umtentwini		1						1	1
Port Shepstone				2					2

	Private Houses	Comm. Props.	Dev.Res. Props.	Main Road	Minor Rd /Car Park	Agri. Land	Road Bridge	Rail Bridge	Railway
Port Shepstone, Station Bay					2				
Port Shepstone, Lucky Dip Bay		1			1				
Port Shepstone S									
Mbango									
Oslo Beach									1
Shelley Beach North	1								
Shelly Beach	1	1			1				
St Michaels on Sea		2							
St Michaels on Sea, Orange Rocks to Uvongo	1		1						
Uvongo Beach		2							
Uvongo Beach to Manaba Beach									
Margate		2							
Margate S	1								
Ramsgate N									
Ramsgate, Bilanhlold Riv.		1							
Ramsgate, Mvutshinti River									
Ramsgate S									
Southboom					1				
Marina Beach, Kent Bay									
Marina Beach S		1							
Empanjati									
Trafalgar									
Palm Beach									
Munster									
Portobella									
Port Edward					1				
TOTAL	12	36	3		28		4	8	18

HAZARD RATING FOR GREATER TIDAL INFLUENCE

	Private Houses	Comm. Props.	Dev.Res. Props.	Main Road	Minor Rd /Car Park	Agri. Land	Road Bridge	Rail Bridge	Railway
Durban Bluff, Sloane Road									
Mission Beach									
Anstey's Beach									
Brighton Beach									
Brighton Beach to Mlazi Canal									
Mlazi Canal									
Isipingo Beach									
Tiger Rocks(N)									
Pipeline Beach									
Umbogintwini (S)									
Amanzintoti North									
Amanzintoti Nyoni Rocks to Lagoon									
Amanzintoti Lagoon		1							
Amanzintoti to Doonside Beach									
Doonside Beach									
Doonside Beach S.									
Warner Beach									
Winklespruit Beach									
Illovo Beach						1	1	2	
Karridene							1	1	
Umgababa									
Umgagaba Riv. Mouth							1	2	2
Sunlight Beach							1	1	
Ilfracombe N									
Umkomas							1	1	
Widenham									
Mahlangwa Riv. Mouth								2	2

	Private Houses	Comm. Props.	Dev.Res. Props.	Main Road	Minor Rd /Car Park	Agri. Land	Road Bridge	Rail Bridge	Railway
Clansthal									
Green Point Manba Alley to Black Rks									
Freeland Park									
Mpambagani Riv. to Scottburgh South									
Scottburgh South									
Park Rynie									
Mzinayi Riv. Mouth							2	2	
Kelso, Station Bay									
Kelso Pennington Beach									
Pennington									
Sezela		2							
Ifafa Beach								1	
Elysium							2	2	
Mtwalane									
Hibberdene									
Hibberden, Pleasant Valley									
Woodgrange									
Umzumbe				1			2	2	
Umzumbe									
Kellerman Rock		1							
Banana Beach N									
Banana Beach to									
Bendigo Sunwich Point									
Bendingo Sunwich Port									
South Point									
Sea Park									
Umtentwini								1	1
Port Shepstone							1	1	

	Private Houses	Comm. Props.	Dev.Res. Props.	Main Road	Minor Rd /Car Park	Agri. Land	Road Bridge	Rail Bridge	Railway
Port Shepstone, Station Bay									
Port Shepstone, Lucky Dip Bay									
Port Shepstone S									
Mbango									
Oslo Beach									
Shelley Beach North									
Shelly Beach									
St Michaels on Sea									
St Michaels on Sea, Orange Rocks to Uvongo									
Uvongo Beach									
Uvongo Beach to Manaba Beach									
Margate									
Margate S									
Ramsgate N									
Ramsgate, Bilanhlold Riv.									
Ramsgate, Mvutshinti River									
Ramsgate S									
Southboom									
Marina Beach, Kent Bay									
Marina Beach S									
Empanjati									
Trafalgar									
Palm Beach									
Munster									
Portobella									
Port Edward									
TOTAL	4	1		1	12	17		5	

HAZARD RATING NATAL SOUTH COAST

HAZARD	SUM	SUM/n (unit vuln.)	REGIONAL UNIT VULN. (scaled by minimum)
Extreme events	115	2.09	115
Increased erosion	63	1.15	63
Greater tidal infl.	41	0.74	41
Raised groundwater	2	0.036	2
Flooding and innund.	1	0.018	1

n = number of vulnerable locations (55)

INFRASTRUCTURE RATING NATAL SOUTH COAST

INFRASTRUCTURE	SUM	SUM/n (unit vuln.)	REGIONAL UNIT VULN. (scaled by minimum)
Commercial property	62	1.13	28.25
Minor roads	46	0.83	20.75
Railway	34	0.62	15.5
Rail bridge	27	0.49	12.25
Private housing	17	0.31	7.75
Road bridge	16	0.29	7.25
Main road	11	0.2	5
Developing res. land	7	0.13	3.25
Agricultural land	2	0.04	1

APPENDIX 3

COMBINED RISK RATINGS FOR THE SOUTH CAPE COAST AND THE NATAL SOUTH COAST

RELATIVE LOCATION RATING FOR THE SOUTH CAPE COAST AND THE NATAL SOUTH COAST

LOCATION	TOTAL RATING
Groot Brak River	48
Wilderness	47
Stilbaai	38
Knysna	37
Plettenburg Bay N/ Keurbooms Riv. Mouth	32
Sedgefield	31
Natures Valley	30
Plettenburg Bay S.	23
Klein Brak River	23
Hartenboss	17
Umzumbe	13
Clansthal	12
Gouritzmond	11
Port Shepstone	10
Umgababa Riv. Mouth	9
Walker Point/Buffels Bay	8
Anstey's Beach	8
Brighton Beach	8
Umkomas	8
Sezela	8
Hibberden, Pleasant Valley	8
Bay View	7
Isipingo Beach	7
Umgababa	7
Mission Beach	6
Mahlangwa Riv. Mouth	6
Scottburgh South	6
Mzinayi Riv. Mouth	6
Elysium	6
Margate	6
Pipeline Beach	5
Illovo Beach	5
Umtentwini	5
Shelley Beach North	5
Ilfracombe N	4
Kelso Pennington Beach	4
Tiger Rocks (N)	4
Glentana & Outeniqua (S)	4
Hibberdene	4
Port Shepstone, Station Bay	4
Herolds Bay	3
Mosselbay	3
Durban Bluff, Sloane Road	3
Karridene	3
Sunlight Beach	3
Banana Beach N	3
Keurboomstrand	2
Flat Rock Beach	2

Bothastrand	2
Tergniet & Reebok	2
Boggoms Baai	2
Vleesbaai	2
Jongensfontein	2
Witsand, Port Beaufort, & Breerivier	2
Mlazi Canal	2
Green Point Manba Alley to Black	2
Park Rynie	2
Oslo Beach	2
Shelly Beach	2
St Michaels on Sea	2
St Michaels on Sea, Orng Rks to Uvongo	2
Uvongo Beach	2
Kleinkrantz	1
Amanzintoti Nyomi Rocks to Lagoon	1
Amanzintoti Lagoon	1
Doonside Beach S.	1
Warmer Beach	1
Widenham	1
Freeland Park	1
Ifafa Beach	1
Umzumbe Kellerman Rock	1
Bendingo Sunwich Port	1
South Point	1
Sea Park	1
Port Shepstone S	1
Margate S	1
Ramsgate, Bilanhlold Riv.	1
Southboom	1
Marina Beach S	1
Port Edward	1
Noetzie	0
Brenton on Sea	0
Victoria Bay	0
Voorbaai	0
Diastrand	0
Danabaai	0
Brighton Beach to Mlazi Canal	0
Umbogintwini (S)	0
Amanzintoti North	0
Amanzintoti to Doonside Beach	0
Doonside Beach	0
Winklespruit Beach	0
Mpambagani Riv. to Scottburgh South	0
Kelso, Station Bay	0
Pennington	0
Mtwalane	0
Woodgrange	0
Banana Beach to Bendigo Sunwich Point	0
Port Shepstone, Lucky Dip Bay	0
Mbango	0
Uvongo Beach to Manaba Beach	0
Ramsgate N	0
Ramsgate, Mvutshinti River	0
Ramsgate S	0
Marina Beach, Kent Bay	0
Empanjati	0

Trafalgar	0
Palm Beach	0
Munster	0
Portobella	0

COMBINED HAZARD RATING

HAZARD	REGION	UNIT VULNERABILITY	OVERALL UNIT VULNERABILITY (scaled by minimum)
Extreme events	Cape	5.03	279
Raised groundwater	Cape	3.38	187
Greater tidal infl.	Cape	2.65	147
Flooding & inund.	Cape	2.23	123
Extreme events	Natal	2.09	115
Coastal erosion	Cape	1.85	103
Coastal erosion	Natal	1.15	63
Greater tidal infl.	Natal	0.74	41
Raised groundwater	Natal	0.036	2
Flooding & inund.	Natal	0.018	1

COMBINED INFRASTRUCTURE RATING

INFRASTRUCTURE	REGION	UNIT VULNERABILITY	OVERALL UNIT VULNERABILITY (scaled by minimum)
Private housing	Cape	3.73	93
Minor roads	Cape	2.61	65
Dev. res. property	Cape	2.27	56
Main roads	Cape	1.77	44
Commercial prop.	Cape	1.62	40
Commercial prop.	Natal	1.13	28
Road bridges	Cape	1.00	25
Minor roads	Natal	0.83	20
Rail bridges	Cape	0.81	20
Agricult. land	Cape	0.73	18
Railway	Natal	0.62	15
Railway	Cape	0.53	13
Rail bridges	Natal	0.49	12
Private housing	Natal	0.31	7
Road bridges	Natal	0.29	7
Main roads	Natal	0.20	5
Dev. res. property	Natal	0.13	3
Agricult. land	Natal	0.04	1